NASA SP-5118

TECHNOLOGY UTILIZATION

HOLOGRAPHY

A SURVEY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA SP-5118

HOLOGRAPHY

A SURVEY

By
David D. Dudley

Prepared under Contract NASW-2173
by
Computer Sciences Corporation
Falls Church, Virginia

Technology Utilization Office 1973
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

For sale by the Superintendent of Documents,
U.S. Government Printing Office, Washington, D.C. 20402
Price $1.70 Stock Number 3300-00546
Library of Congress Catalog Card Number 73-600236

Foreword

This is one of a series of Special Publications issued by the National Aeronautics and Space Administration as part of its Technology Utilization Program. That program was undertaken to share the benefits of aerospace and related research with other potential users of it in engineering, science, and industry.

Holography is one of the newest and most intriguing of the many new techniques with which NASA has been concerned, and now seems likely to become extremely helpful in many human endeavors. The author has reviewed the development of holography and surveyed the current state of the art in recording and displaying information, microscopy, motion pictures, and television.

In addition to optical holography, this survey has embraced microwave, acoustic, ultrasonic, and seismic holography. Additional chapters deal with data processing, storage, pattern recognition, and computer-generated holography. A glossary has been included for readers unfamiliar with the terminology, and those who want additional information will find the references a useful guide to it.

Director
Technology Utilization Office

Contents

CHAPTER 1

Introduction to Holography

Imagine yourself looking at an exhibition of still life photography; a conventional photograph of Michalangelo's "La Pieta" is on the wall directly in front of you and a similar sized covered frame is to your right. In the conventional photograph you see a two-dimensional image, although the illusion of depth, form, and shape has been achieved through imaginative lighting of the statue. If the lighting were flat, the statue would look more like a photograph of a drawing than a three-dimensional object with shape and form.

Now imagine that the frame to your right is uncovered. The transparency in the frame is a "hologram" and could be illuminated from the rear by either a conventional incandescent light source or a source of coherent (in-phase) light such as a laser. Using conventional light, the hologram appears to have a featureless cast with no discernible image. However, selecting the proper coherent light source reveals an exact replica of the original "La Pieta" instead. This image is truly three-dimensional, because each eye sees the statue's image through a different area of the hologram and thus perceives it from a different aspect. As your head and eyes move, the image changes in perspective, exactly as the original statue would appear to an observer moving about and looking through a window the same size as the frame.

If you were to cut the conventional photograph of "La Pieta" in half, you would of course see only half an image. With the hologram, however, you could still see the entire statue, although with some loss in resolution.

Both the human eye and camera film as normally exposed through a lens record only intensity; the hologram records the phase information in the wave as well. The eye lets us see form because each eye perceives a slightly different image and the brain acts as a computer to report the differences as depth; in a photograph, whatever effect of depth is created is due to lighting techniques, and flat lighting gives photographs that are relatively featureless. The hologram, on the other hand, because it supplies phase information as well as the intensity, gives true depth perception in three dimensions.

The three-dimensional and image redundancy characteristics of the hologram are but two of its fascinating aspects. Contemporary holographic techniques for recording and viewing objects are revolutionizing many engineering, production, and display problems.

FIELDS FOR HOLOGRAPHIC APPLICATIONS

These current and potential holographic applications can be of value in the following fields:

- Law Enforcement and Crime Prevention
- Banking and Economic Control
- Food Production, Processing, and Distribution
- Wearing Apparel and Household Furnishings
- Communications, Data Processing, and Transfer
- Education and Welfare
- Transportation
- Entertainment, Recreation, and Advertising
- Building and Construction
- Manufacturing and Instrumentation
- Business and Services
- Medicine and Public Health
- Chemical Industry, Drugs, and Plastics
- Resource Maintenance and Management
- Aerospace Exploration and Utilization
- Defense

The three-dimensional effect aroused a flurry of interest in the potential of three-dimensional movies and other forms of mass entertainment in the 1960's. The problems and some of the attempts to overcome them are discussed in chapter 7. Other uses based on

the phenomenon are widespread, and some are commercial. For example, it is possible to detect stresses or deformation in machine parts or printed circuits, or to detect flaws in integrated circuitry. The method has even been studied for possible use in a memory system for off-track betting.

Holographic techniques make it possible to store a large amount of information in a small space, 200 times as much as microfilm or microfiche, and to read it back at higher rates of speed. More than one image can be recorded on a single film area and read back with minimal cross-talk. The information stored, both in density of storage and speed of readout, is higher than that needed by present computers or library storage systems. Holography should lead to even faster computers and help solve the problem of what to do with the mass of material pouring into our libraries.

A holographic record of a fingerprint on a card cannot be identified as a fingerprint by visual means, but the hologram can be compared with the individual's print for identification purposes. Such security equipment has already been designed. A further step is to "scramble" the hologram according to a code pattern so that unique equipment must be used to reconstruct the fingerprint record.

The principles of holography have been applied to other types of wave systems, such as acoustic, radar and ultrasonic systems. They offer promise in medicine as a noninvasive method for studying internal portions of the body. Tumors, for example, can be investigated by acoustic techniques.

A holographic technique has been used for "image deblurring"–improving the readability of unsharp images. This is akin to noise reduction after the fact, although holograms give high signal-to-noise ratios.

For several years, holographic techniques have been used to map terrain with radar waves, and also have applications in earth surveillance for agriculture, forestry, and urban problems.

One of the problems with honeycomb structural materials that combine strength with low weight is the bonding of the skin surfaces to the honeycomb core. Laser holography provided an answer, since comparison of an original hologram and one made after the panel had been heated showed fringes indicating lack of bonding. A similar comparison directly and then under slight vacuum to cause a stress has been used to examine tires for trucks and aircraft, and for recapping. Lack of bonding, breaks, or foreign particles can be observed. The method is relatively rapid. The machine may find wider use as Federal requirements for tires become more restrictive. The acoustic holographic method used for soft tissues has also been applied to the examination of steel blocks up to 19 in. thick. A holographic method for measuring the thickness of films deposited on a surface has been worked out and might be helpful in the application of thin plastic coatings to containers where control of thickness is important.

A number of possibilities for holography exist in particle measurement and control. For example in one method of removing sulfur compounds from the gases in coal-fired boilers, a cloud of pulverized limestone is blown into the chamber. The uniformity of this cloud, and hence its effectiveness, can be studied by holographic methods. Particle studies have been used for determining the droplet pattern in carburetors, and might improve the common aerosol spray can process. There are also other spray processes where holographic information might be helpful, including various types of industrial coating procedures.

By holography of the retina of the eye, glaucoma and other difficulties can be determined, even in the presence of cataracts. Since the image is three-dimensional, various layers can be studied from the hologram, which also provides a permanent record for later reference.

For the training of astronauts, a method was developed that caused the image to appear larger and nearer as the "approach" took place. Another method, developed to produce a wider angle of display at the sacrifice of some spatial resolution, is being investigated as a system of air traffic display and control for the Federal Aviation Administration.

A Visual Information Processing System uses computer-generated color output display. Laser sources capable of producing 5-micron size dots will be used by the computer to read the holograms.

The advertising profession was not slow to recognize the possibilities of the new method of presenting illustrative material. At the opening of a new automotive building, a "display case" showed alternately the body of a new car and that of a Napoleonic coach, apparently filling the space. There were four "windows," actually holograms, so a spectator could walk completely around the exhibit. From time to time, the space was illuminated with diffused light to show that it was actually empty.

Holography is part of a system being developed for producing a two-dimensional color TV program from a tape for home viewing. A relief type hologram is used as a master tape, and the final tape is embossed from the master. The resulting tape is resistant to the effects of scratches. It is expected to sell for about $3 and the playback unit may sell for about as much as a color TV set.

A holographic camera developed for moon studies is rugged enough for earth service as well. It has shown a capability for microscopy of the holographic image throughout the working space; hence a single exposure will give far more information than will a photograph through a conventional microscope. A commercial holographic microscope has been developed that can make a series of exposures showing, for example, crystal growth, bacterial movement, and other surface changes under various conditions.

A major practical application of holography began with the discovery that two or more holographic images could be compared precisely by simply superimposing them by one of many methods. The same film may be used for both, or separate films employed, or the holographic image superimposed on an actual object. A study of this type has led to a 30-percent improvement in the intensity of a xenon arc lamp. The principle has also been used in evaluating the contours of a 9-ft-diam microwave antenna to an accuracy of 0.001 in.

It is clear that holograms properly spaced in time could aid in studies of vibration and shock, both from a theoretical and a commercial standpoint. Their use avoids sensor problems characteristic of other methods. One result has been a new theory for the premature failure of thin shells under a buckling stress. The method does not involve contact and permits the entire surface to be mapped at one time. Fluid flow, fluid density, and fluid temperature measurement are other uses for holography, and do not demand the insertion of probes that would change the pattern.

These examples are all related to nondestructive testing, a field where there are many uses for holography. Titanium welds, honeycomb structures, solid rocket propellants, the formation of microcracks, and contamination by space particles are all of interest to NASA and are being studied. Turbine blades designed for a jet engine were found to have a resonance in a dangerous range. Redesign, checked again by holographic methods, avoided possible engine failure. Other engine parts are also tested with successful results. Bearings are being checked at full speeds by the Navy to reduce the possibility of service failures.

If incipient cracks set up surface disturbance patterns, they can often be detected by holography. Initially invisible stress corrosion cracking in titanium was investigated in this manner, and a radial crack from a saw cut was also shown. A different holographic technique was used in the study and development of a speaker cone to show the patterns at different loadings and frequencies.

Motion pictures of holograms have been made to show fringe changes with time. Making three-dimensional holographic movies has proved difficult except for specialized applications; proposed solutions are being explored and a movie producer has announced that he will employ a patented process to make a holographic movie using laser lighting. Television poses another problem because of the bandwidth presently needed for the information in a hologram. If improved methods for movies can be worked out, they may make television holography more likely.

The word "holography" was coined from the Greek words *holos* (whole) and *grapho* (to write) by its inventor, Dr. Dennis Gabor, Nobel Physics Laureate of 1971. It may be defined as the science and technique of recording (or otherwise using) all the information content of waves transmitted, reflected, or scattered from objects. These objects can be either stationary or moving in translation, rotation, or vibration.

Holography is not restricted to specific classes of waves. It can involve the entire spectrum of transverse electromagnetic energy—from long radio waves, through optical wavelengths, to x-ray wavelengths; as well as the spectrum of longitudinal wave energy, from long wavelength seismic disturbances, through acoustic sonar waves, to the very short ultrasonic wavelengths.

The material that photographically records the wave information from a test object is called a "hologram." When such a hologram is properly illuminated, a three-dimensional image of the original object can be formed or reconstructed. The entire system forming the hologram and reconstructing the object's image is called a "holographic system." The equipment used in forming the hologram is sometimes referred to as a "holocamera," and the process

of image formation as "wavefront reconstruction." In 1948 Dr. Gabor developed the underlying principles of holography into a comprehensive theory that the amplitude and phase information of a reflected or scattered optical wave from an object could be recorded by interaction or "interference" between the object wave and a coherent background reference wave (ref. 1).

It might be useful at this point to reflect on the differences between holography and photography. Photography is basically a method of recording only the two-dimensional irradiance (or intensity) distribution of an image. Each "scene" consists of a large number of reflecting or radiating points of light, and the waves from each of these elementary points all contribute to a complete wave–the "object" wave. This complex wave is transformed (or focused) by the optical lens so that it collapses into an image of the radiating object, which is the image recorded on the photographic emulsion. In holography, on the other hand, it is not the optically formed image which is recorded, but the totality of object wave itself. This wave is recorded so that a subsequent illumination of the record with the reference wave serves to reconstruct the original object wave, not just its intensity, and even in the absence of the original object. The observer of this reconstructed wavefront sees an object or scene that is practically indiscernible from the original. Recording the object wave rather than the object image constitutes the basic difference between holography and conventional photography.

Gabor's idea was limited by available light sources and lay dormant until 1962-1964, when Leith and Upatnieks (ref. 2) demonstrated that a coherent light beam from a laser could be split to form both the object and the reference beam, and that interference between the reference and the object wave (either transmitted or reflected) from the subject could be recorded on a photographic plate (hologram) to show both its amplitude and phase.

This long delay between discovery of the theory and its experimental demonstration stemmed from the inadequacy of light sources before the advent of the laser. If successful "interference" is to occur between two traveling waves, the path difference between the two waves from their source to their point of interaction must be less than or equal to the coherence length of the wave radiation. The incoherent incandescent or arc light sources had very broad spectral or color bandwidths; although they could be filtered to a narrow, nearly monochromatic bandwidth, almost all their energy was lost in the process. Using these early sources, only very weak holograms with path differences in the order of tenths of millimeters were possible. The first helium-neon gas laser sources had coherence lengths of several centimeters, and gas lasers can now be constructed with coherence lengths of hundreds of meters. This allows path differences of meters, so that the reference beam and object beam paths need not be perfectly compensated in length. Thus, although the laser made holography a practical reality, the type of laser used strongly affects holographic techniques. For example the short coherence length of most pulsed laser sources (compared to continuous wave lasers) still acts as a constraint on geometry when pulsed lasers are used for holographic interferometry and photography.

SURVEY APPROACH

This survey describes current and completed NASA efforts in holography, along with some background on other efforts to provide perspective on the entire field. Twelve areas or disciplines within holography are identified in table 1. Primarily these are functional categories–engineering or scientific applications that can be satisfied through holographic techniques–but some are also related to the specific techniques or to particular wavelengths used in forming holograms or holographic material.

TABLE 1.–*Holography Categories Key*

Discipline	*Chapter key*
Optical Holographic Recording	Chapter 3
Optical Holographic Display	Chapter 4
Optical Holographic Microscopy	Chapter 5
Optical Holographic Interferometry	Chapter 6
Optical Motion Picture/Television Holography	Chapter 7
Microwave Holography	Chapter 8
Acoustic and Ultrasonic Holography	Chapter 8
Seismic Holography	Chapter 8
Holographic Data Processing and Storage	Chapter 9
Holographic Data Processing and Pattern Recognition	Chapter 9
Holographic Optics	Chapter 10
Computer-Generated Holography	Chapter 10
Summary of State of the Art	Chapter 10

Chapter 2 presents additional information on single exposure holographic concepts; it explains how a hologram works and some of the basic characteristics and classifications of holograms. Practical techniques for producing holograms, and some of their limitations, are also included. Appendix A describes in detail how the hologram of a point, called a zone plate, can reconstruct itself, while appendix B offers a more rigorous elementary mathematical demonstration of the generation and reconstruction of various holographic images and of the reciprocity of a hologram. Appendix C describes the properties of several classes of holograms and discusses holographic performance parameters. Appendix D provides some detailed background for understanding holographic optical data processing and filtering.

The variety of present and potential applications of holography is dealt with in chapters 3 through 9 by the categories listed in table 1 (see the "chapter key"). Chapter 10 contains a more detailed discussion of these discipline areas and a concise summary of the state-of-the-art by discipline. Where necessary for better understanding, explanations of techniques and background also appear in the discussion of each discipline.

No separate chapter is included for holographic optics or computer-generated holography, but these areas are included in the holographic state-of-the-art chart (ch. 10) and in the applications summary matrix (table 2). Although these areas have great potential, NASA has not been active in them and for the most part they are in an early research and development phase (refs. 3 and 4). The discussion of applications and technology in subsequent chapters is generally in two main sections: NASA Research and Development and Commercial Endeavors. Research and development applications include holographic

TABLE 2. - APPLICATIONS SUMMARY MATRIX

HOLOGRAPHIC AREAS OF DISCIPLINE	Law Enforcement & Crime Prev.	Banking & Economic Control	Food Prod., Proc. & Distrib.	Clothing & Household Furnish.	Communications, Data Proc. & Transfer	Education & Welfare	Transportation	Entertainment, Rec. & Advertising	Building & Construction	Manufacturing & Instrumentation	Business & Services	Medicine & Public Health	Chemical Indus., Drugs, Plastics, etc.	Resource Maint. & Management	Aerospace Exploration & Utiliz.	Military & National Protection	Research & Development	Technology Contribution
Holographic Recording			★			★	★		★			★	★		●	★	★	NASA
							★	★		●		●		●	●	●	●	Other
	★	★	★	★		★	★	★		★	★	★	★	★	★	★	★	Pot.
Holographic Display						★	★	★							●	★	★	NASA
				★		■	●	■	★		★	★		★	★	●	■	Other
	★	★		★	★		★					★		★	★	★		Pot.
Motion Picture or TV Holography							★		●	★		★			●	★	★	NASA
																		Other
								★				★			★	★	★	Pot.
Holographic Microscopy	★				★		★	●	★	★		★	★		●	★	★	NASA
						★				★		■	★		★			Other
					★			★				★	★				★	Pot.
Holographic Interferometry					★		★		★	★			★	★	■	●	★	NASA
							■	●	★	■		●			●	●	★	Other
			★		★	★	★	★	★	★		★	★	★	★	★	★	Pot.
Microwave Holography																		NASA
							★		★						★	■	★	Other
	★		★						★	★		★		★	★	★	★	Pot.
Acoustic and Ultrasonic Holography						★			★	★		★			●	★	★	NASA
			★				★	★	●	●		■	★		●	●	●	Other
			★			★	★		★	★		★	★		★	★	★	Pot.
Seismic Holography																		NASA
							★							●			★	Other
							★							★		★	★	Pot.
Holographic Data Storage & Retrieval																		NASA
														★		●	★	Other
	★	★	★		★	★			★		★	★		★	★	★	★	Pot.
Holographic Data Proc. & Pattern Recognition	★	★			★	★		★		★	★	★		★	●	★	★	NASA
	■	★	★	★	■	★	★				★	★		★	★	★	★	Other
	★	★	★	★		★	★	★	★		★	★	★	★	★	★	★	Pot.
Holographic Optics																		NASA
																		Other
								★		★				★	★	★	★	Pot.
Computer Generated Holography																		NASA
																		Other
				★			★		★	★					★	★	★	Pot.

Legend:

■ Commercial System, Application

● R&D Application

★ Potential Application

devices, systems, or techniques that gather data not obtainable in any other way, or at least collect it more effectively. In a few cases these have practical uses. Commercial endeavors include commercially marketed devices available and developmental holographic devices or systems of proven industrial value. Included under both sections are some potential applications, techniques, and devices which have not yet demonstrated practical usefulness, but which show real promise. Several of the commercial items are related to previous contract work done for NASA.

Table 2 shows at a glance the scope of present applications and the projected use of a given holography discipline in each field of application. Because the practical applications of this new technology are so recent, special emphasis is given in this survey to predicted or potential applications, documented by references on their initial experimental stages. Some applications have been suggested by extrapolation from reviews of current work. There is simply not enough experience in the field for a meaningful cost analysis of commercial holography, although it seems clear that several corporations are saving money and manpower by using holographic aircraft panel and jet engine testing and holographic contour mapping.

The interaction between each developed holographic discipline and the fields of application is shown by the three codes in table 2. Present commercial holographic systems, devices, or equipment that are practical for a given application field are designated by a solid box. This category includes systems developed through NASA that have led to improvement in the design and operation of practical devices. Current equipment in a research and development status which shows considerable promise of commercial use is shown by a black dot, and potential applications of either present holographic R&D equipment or of holographic concepts, techniques, or methodology are shown by a star. The source of each discipline (NASA, Other, or Potential), as described in chapters 3 through 9, is also shown in the matrix.

NASA HOLOGRAPHIC CONTRIBUTIONS

The NASA Centers are oriented to basic and applied research; thus their primary goal is to discover and develop new techniques, materials, or equipment for present and future generations of aerospace and related systems. All of these endeavors require highly sophisticated data storage, data processing, image forming, scanning, data communications, tracking, and optical beam steering. In addition, many final systems, subsystems, and components must be tested during design and construction by nondestructive direct methods.

Table 2 and the subsequent chapters of this survey show that NASA's contribution to holography has been direct and substantial. Particularly promising is the developmental work on holographic data storage and data processing systems, which, because of their compactness and extremely high-density data storage characteristics, will be ideally suited for future mass data storage needs related to earth resources and environment, law enforcement, and medical records. The extent of NASA's work in holographic interferometry also indicates the importance of nondestructive holographic testing in meeting space and launch vehicle systems test requirements.

NASA's work in holography for aerospace technology already has led to some nonaerospace applications. For example, early work to develop cold-spray and rocket combustion holocameras by the Jet Propulsion Laboratory (JPL) in conjunction with the Department of Defense (DOD) has led one contractor into a series of development efforts with the Environmental Protection Agency to construct equipment for analyzing processes inside commercial furnace stacks and domestic heating systems as a pollution control measure. Each NASA-funded effort could become such a "seed" development in holograpny. This natural transfer of information and engineering skills is taking place continuously in all aerospace projects, and is being deliberately accelerated through the activities of the NASA Technology Utilization Office (ref. 5).

CHAPTER 2

Principles of Holography

Holography has been called lensless photography, and in a sense this is correct. However, its differences from photography are more numerous and important than its similarities (ref. 6). We can think of holography as being a method of "stopping" a traveling wave front and capturing or storing it on film; the reconstruction process then "starts up" the wavefront again after an interval of time and possibly a change of position. This "started up" wavefront can then form an image or be viewed just as it originally appeared when radiated or reflected from the subject.

For clarification, let us review some basic facts about wave behavior. Any electromagnetic wave, including a light wave, has both an amplitude and phase value at a given time and place. The amplitude of an invisible electromagnetic wave is exactly one-half the height from peak to trough. The amplitude of a visible ocean wave is similarly determined. Phase is a measurement of which part of a wave (from one peak to the next succeeding peak) is passing through a given point at a given time. The energy contained in an ocean wave is proportional to the square of its amplitude; light wave energy or intensity is measured in the same way.

Now consider a block of wood floating on the ocean. As the peaks and troughs of a wave pass through, the block is alternately elevated or depressed in relation to the normal ocean surface. The instantaneous displacement of the block is dependent on the wave's amplitude and phase.

Finally try to recall the effect when two "trains" of ocean waves collide. The new single wave train which forms is usually of a different amplitude than either of the waves that formed it. Where the phases reinforce each other (peak on top of peak), their amplitudes tend to add, and constructive interference occurs; where the phases oppose each other (peak on troughs), their amplitudes tend to subtract, and destructive interference occurs.

Light waves behave exactly as do ocean waves, and the results of their interference (both constructive and destructive) can be made visible on photographic film. Ordinary photographic film responds to the intensity of light to which it is exposed. The density of the developed film can, through proper processing, be made proportional to the intensity of squared amplitude of the light wave pattern that strikes it. This is conventional photography. Using ordinary photography, there is no way to make the film density vary with the phase of the light striking it; through holography, this can be done. Because the hologram can store both amplitude and phase information, it is able to effectively record a wavefront impinging upon it.

The simple representation of holographic fringe formation in figure 1 shows how the hologram stores phase information. A plane coherent wavefront strikes the prismatic wedge from the left. This wedge by refraction splits up the front into an "object" and a "reference" wave. These two waves are analogous to the colliding ocean waves just described, except that they are tilted at an angle to each other. For example consider the object and reference waves to be of equal amplitude; since they originate from the same coherent source wave, they are of equal frequency and wavelength.

The paths and intersection of these two waves can be followed by the fronts indicated in the figure. For example, notice their intersection or interference at point P of the hologram film plate (fig. 1b). Fronts F_O and F'_O represent the position of two successive amplitude peaks of the object wave at an instant of time, and F_R and F'_R are similar peaks of the reference wave (the distance between F_O and F'_O and F_R and F'_R is their wavelength). Between the wedge and the film plate (fig. 1a), we can visualize a space filled with similar successive wave peaks and with wave troughs midway (1/2 wavelength) between each

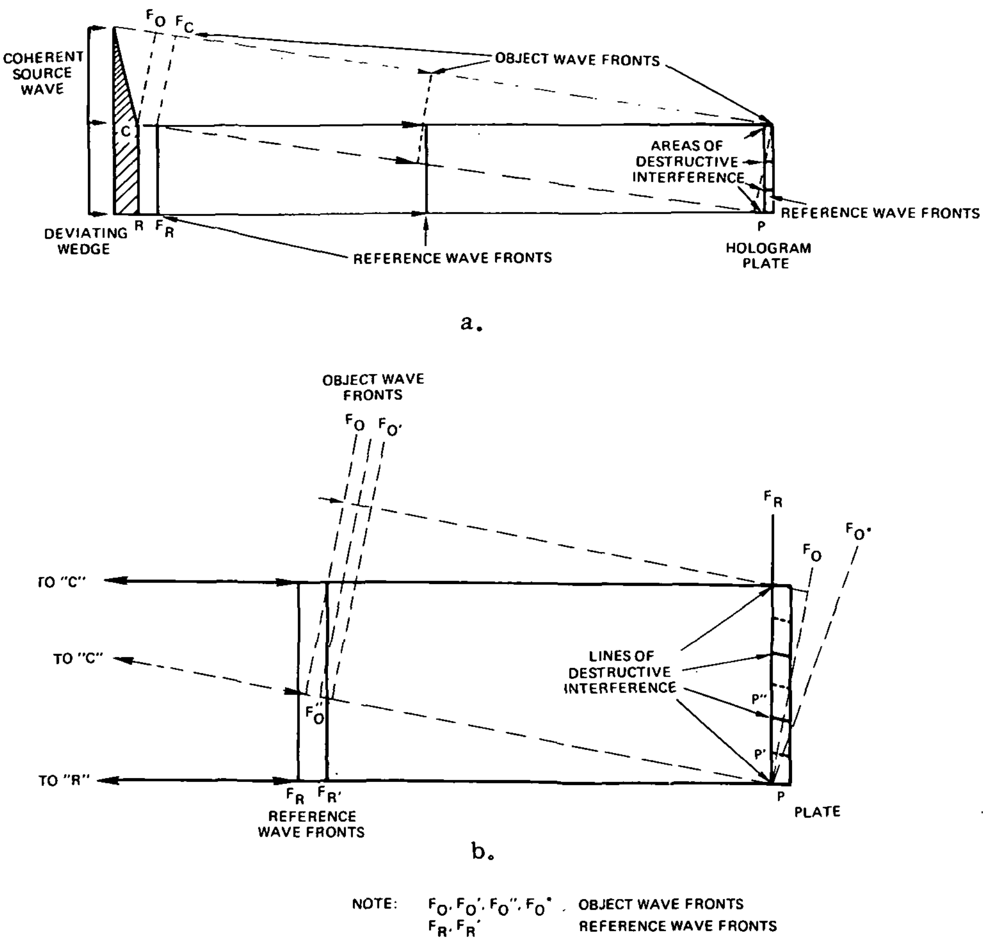


FIGURE 1.–Holographic fringe formation.

peak. If the distances *CP* and *RP* differ by an even number of half wavelengths, their interference is constructive at point *P* (peak on peak); but if they differ by an odd number of half wavelengths, their interference is destructive at point *P* (peak on trough) (refs. 7 and 8). The figure shows the latter condition. This destructive interference would be represented on the hologram by a dark line, called a "dark fringe."

As we travel up the plate, observe that the distance from the first front F_O (fig. 1a) to the plate is shorter than before, while the distance from *CR* (fig. 1a) remains the same. At some point higher up on the film plate, P', a constructive interference (peak on peak), takes place; further up, a second destructive interference takes place at p'', and so on up the plate (fig. 1b). In this manner, a series of dark line fringes of equal separation are produced on the film.

If the phase of the object wave is shifted so that the peak occurs at F''_O (somewhere between F_O and F'_O), while the phase of the reference wave remains the same, then the position of the fringe lines will shift on the film plate, but their separation will not change. Thus by the interference of the two waves it is possible to record a relative phase change between them as well as their amplitudes. This is the basis of holography: The exposed photographic film plate has recorded *both* the amplitude and phase of the object wavefront relative to the reference wavefront.

If the angle of tilt between the two waves (fig. 1b) is increased, as represented by wavefront F_O*, then the distance up the plate from *P* at which the next dark fringe occurs will be shortened; hence more interference fringes will occur per unit of length. This means that the resolution capability of the film (its

capacity to record fringe lines per unit length) must be higher.

The discussion thus far has assumed that the waves forming the object and reference front are exactly the same length and, although shifted in relative phase, remain constant during exposure of the photographic plate or film. But if the relative phases of the two interfering waves are changed during the exposure, then the fringe positions also shift during exposure. If such a shift is random and amounts to a displacement of one-half the distance between dark fringes, the fringe pattern will be almost completely washed out. However, when fringe shifts are regular during an exposure, it is sometimes possible to record an average of the fringe patterns. This is the basis for time-averaging holographic interferometry.

Relative phase shifts between two waves occur in two principal ways: (1) by a change in the distance either wave travels from the source to the film or (2) by a change in the index of refraction of the medium (usually an air pressure or temperature change) through which either wave travels. A third type of phase change can be caused by a change in the frequency of either the source or the object wave, as when it is reflected from a moving surface.

If a transparent small subject is placed completely in the path of the object beam (fig. 2), the absorption and index of refraction of this subject will produce phase and amplitude changes in the wavefront passing through it. The resultant scattered object wave interferes with the plane reference wave to produce an irregular interference pattern rather than regular fringe lines. This recorded pattern will form a hologram of the transparent subject (ref. 7).

An arrangement such as this, using a separate reference and object beam, is called two beam holography. Subjects can also be placed directly in the path of the reference beam (with no separate object beam formed); this is referred to as inline holography.

HOW AND WHY THE HOLOGRAM WORKS

The appearance of any object, no matter how complicated, is a sum of reflecting or scattering points in three-dimensional space. When that object is coherently illuminated and a hologram is recorded, each point will form its own individual interference pattern. The interference pattern or hologram of a point is called a zone plate. Appendix A explains in detail the formation of this zone plate and how, when the laser beam illuminates the zone plate, a virtual and a real image of the original point is reconstructed. Since the total holographic pattern from an object is the superposition of all these individual zone plate patterns, the proper reillumination of the hologram will reconstruct both a virtual and a real image of every point on the original object. The sum of the virtual point images will reconstruct a perfect replica of the original object for the viewer. The sum of the real point images will allow the projection and formation in space of a three-dimensional image of the original object. Both of these properties are used extensively in holography (refs. 9 through 11).

This effect for two beam holography of a complex object is illustrated in figure 3. Here, a coherent object beam strikes the front (heavy line) surface of the double-triangular prismatic object and reflects down to the recording plate, while the reference beam strikes the plate from below. The figure on the left of the recording plate represents both the original object and also the reconstructed virtual image, while the figure on the right is the reconstructed real image. Refer to appendix A for details.

Notice that every point of the reconstructed image is formed at exactly the same distance from the recording plane on the left as the object is located from the plane on the right. This produces an effect called a reversed contour, or pseudoscopic image, since an observer viewing the real image from the right will see only the dark lined surface. Thus he will see a peak where there was a dip on the original and

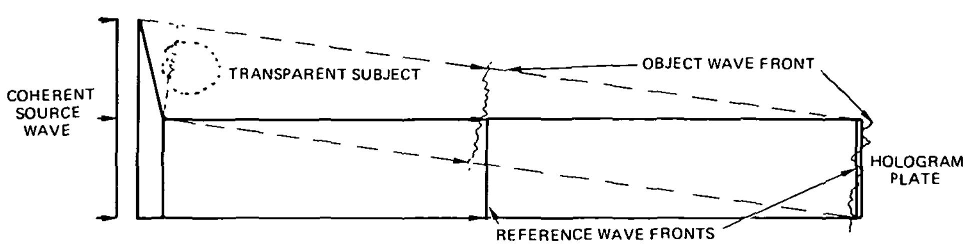


FIGURE 2.–Hologram formation.

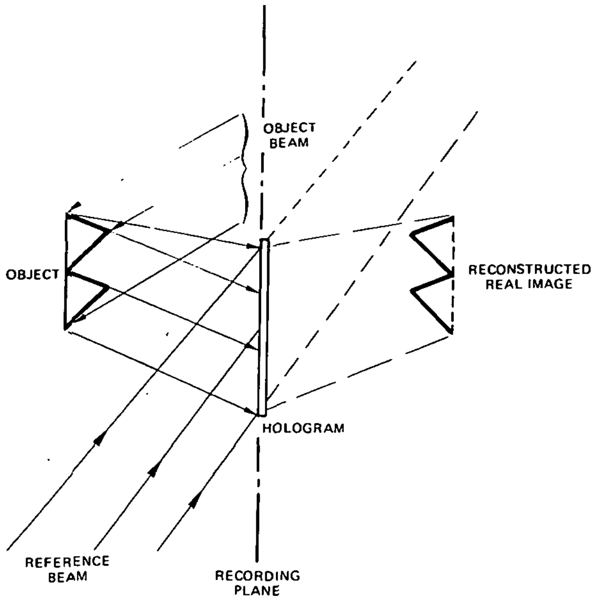


FIGURE 3.–Pseudoscopic image reconstruction.

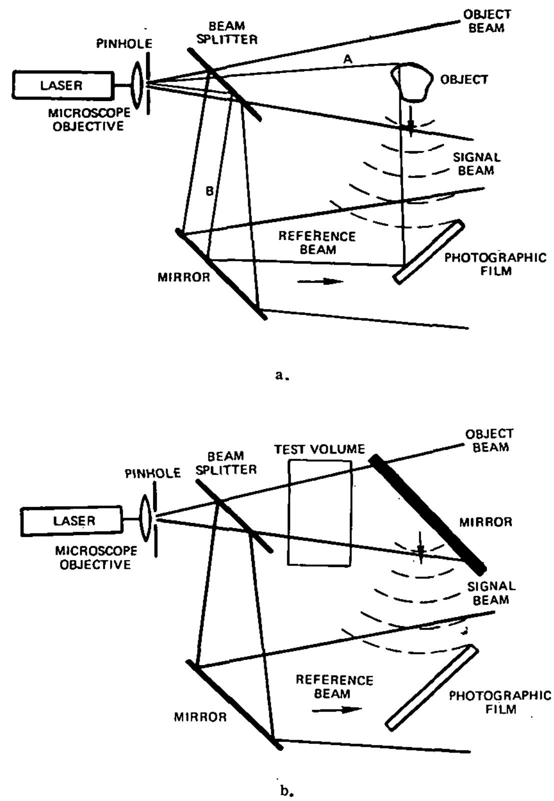


FIGURE 4.–Practical methods for recording hologram.

vice versa. As illustrated by the dotted line on the figure, the baseline will not actually be formed in the real image, so that the reversed order contour is easily observed. This effect becomes even more troublesome with more complicated objects. Normal perspective real images can be formed either by reconstructing a second generation hologram or by using lenses in various configurations (refs. 9 and 12).

PRACTICAL HOLOGRAM PRODUCTION

So far we have talked in theoretical terms about idealized plane reference and object waves, but in reality it is usually practical to use slightly diverging or converging waves in one or both beams of a system. A typical arrangement complete with laser light source, microscope focusing objective, filtering pinhole, beam splitter, reference beam directing mirror, and recording film is shown in figure 4a. As indicated in the diagram, the object reflects or scatters light energy from its surface onto the film to form the object or signal beam, while the reference beam is incident upon the film from the left. The microscope objective and filter improve the clarity of the hologram's interference fringes.

The microscope lens focuses the light to a point at the circular pinhole. The light beam then diverges past its focus point and illuminates the object and film. Any nonplanar light front, including spatial noise, will not focus to a point at the pinhole and hence will be blocked out. Note that the geometries have been arranged so that the reference and object path lengths from the laser are equal.

The alternative arrangement (fig. 4b) is for a transparent object, such as a two-dimensional photographic transparency or a volume of a solid, liquid, or gas. The configuration is the same except that the object has been shifted in the illuminating beam far enough to allow an additional mirror to illuminate the hologram. A typical use is to provide a cross-sectional view through a wind tunnel or ballistic range, where the phase perturbations caused by the pressure flow lines and temperature gradients in the test volume contribute to the hologram. The transparency configuration is also often used for compact data storage and retrieval purposes.

The variation shown in figure 5a puts the pinhole filters beyond the beam splitters and deflection mirrors, providing a cleaner and higher quality hologram. Another variation often used (fig. 5b) is to

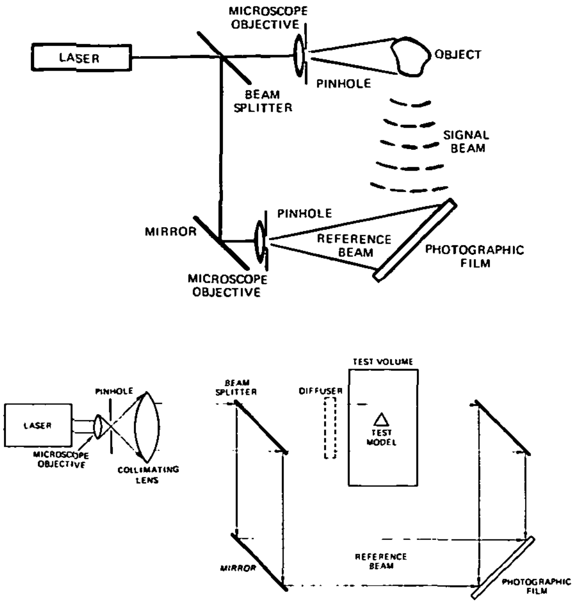


FIGURE 5.–Alternate hologram recording methods.

place a lens just beyond the pinhole filter, which collimates the light passing through the transparent test volume. This arrangement permits production of Schlieren photos, shadowgraphs, and single perspective holograms (ch. 3). The single perspective results from the fact that a given ray through the top and bottom of the test volume strikes separate positions rather than all positions on the hologram recording film; when the top part of the hologram is viewed by the observer, the bottom part of the test volume cannot be seen, and vice versa. Multiple perspective can be obtained in such cases (the property of the normal hologram) by inserting a diffusing screen or scatter plate (fig. 5b) before illuminating the test volume. Some rays will then pass through each point in the test volume and strike each part of the recording film. A diffuse reflection (scattering at all angles from the point of reflection) from a solid object produces the same effect (ref. 12). Surprisingly the hologram reconstruction properly sorts out even these diverse and complex patterns into the correct image of the original object.

BASIC PROPERTIES OF HOLOGRAMS

The most startling quality of the hologram is its formation of both a virtual and a real image as previously described. The virtual image looks identical to the original three-dimensional object, because the actual wavefront amplitude and phase are totally reconstructed. Since each eye sees a slightly different perspective, they construct a three-dimensional stereoscopic image, and movement of the head permits each eye to see a changing perspective as in an actual scene. The real image reconstruction, on the other hand, is pseudoscopic and has inverted contours. Holography repeals no law of optics, so that these holographic images are subject to all the normal optical image aberrations and perturbations, such as spherical aberration, coma, astigmatism, field curvature, and distortion.

Another useful property of the hologram is its reciprocity during reconstruction. This means not only that the object wave be reconstructed by the reference wave (the normal method), but also that the reference wave can be reconstructed by the object wave. This property is essential for optical data processing and for encoding (ch. 9 and app. B).

The reconstructed image on a hologram can also be magnified. This is done by three different methods: (1) the ratio of wavelengths used to reconstruct and record can be changed; (2) the scale of the hologram used to reconstruct can be changed, relative to that used to record; and (3) the hologram can be illuminated by a spherical wave whose radius of curvature is different from that used to record. The last method always produces image aberrations of some sort, but the first two methods can be combined to produce magnified, aberration-free images when plane recording and reconstruction waves are used. However, only one of the reconstructed images (virtual or real) can be produced aberration-free at the same time (ref. 13).

The critical requirements for producing a good hologram are a reference beam, an object beam, a recording light source, a hologram plate, and equipment to direct and form the geometry of the two principal beams. These two beams must be coherent in two ways: (1) their frequencies must be equal and their relative phases to each other must remain constant with time; and (2) all positions of a plane reference wave must be of the same phase at the same time.* These conditions are usually called temporal coherence and spatial coherence respectively (ref. 14).

*This is a restriction on classes of spatially coherent waves.

The laser beam is the only practical optical source that can meet these two conditions, although even laser output is neither completely monochromatic nor exclusively of one frequency. The degree of spread in frequencies (temporal coherence) is usually expressed by a parameter called the coherence length, since path length differences less than the coherence length are required to observe holographic interference effects. If this difference is exceeded, then the fringes produced by the lowest frequencies of the light source wash out those produced by the highest frequencies. Any inequality of path lengths will cause some fringe shift, even if the coherence length is large; thus much effort has been devoted to designing equal path lengths that provide maximum subject depth for hologram recording. Continuous wave lasers are capable of coherence lengths up to a kilometer, but narrow Q-switch lasers needed for holographic interferometry have only recently attained values of between 1 and 10 meters. Careful operation, adjustment, and filtering of laser sources are usually required to attain the coherence properties desired in holography (refs. 14 and 15).

Other important factors in hologram production are the ratio of reference beam to object beam intensity during recording (ref. 16), the relationship between light intensity and exposure time (ref. 17), the geometric arrangement of the object and reference beams as it affects spatial resolution (ref. 18), and the stability (freedom from motion or vibration) of the equipment components. Rigid support, acoustic isolation, and foundations of damped granite tables or sand boxes are usually necessary to ensure equipment stability. (These factors are described in more detail in app. C.)

CLASSIFICATION OF HOLOGRAMS

There are many ways of classifying holograms, each emphasizing different properties. The following eight major classes or sets of categories are commonly used: 1. transmission/reflection mode holograms, 2. thick/thin, 3. volume/plane, 4. color/monochrome, 5. optical/microwave/acoustic/seismic/computer, 6. amplitude/phase, 7. time-average/single- or double-exposure, and 8. sideband/inline. In general, the individual categories of each class include all possible holograms, and these categories may be considered ways of describing or characterizing a hologram. Thus a single sideband, thick, volume, color phase hologram of an object could be recorded using a double exposure technique with optical energy in the reflection mode. (These categories are described in more detail in app. C.)

CHAPTER 3

Single Exposure Holographic Recording

A hologram may be recorded in a single exposure, and single exposures of moving objects may be recorded by very short laser pulses. Work in this area has been carried on both by NASA and by commercial/industrial groups.

NASA has been active in promoting the following types of single exposure holographic recordings:

- holography of microparticles
- rocket engine holocameras
- holography of objects in motion
- aids to practical holography

Commercial and industrial organizations are now developing single exposure systems using conventional and nonconventional recording materials. These holographic recordings are being applied to:

- analyzing pollutants from furnaces, fuel systems, and engines
- studying reacting sprays and dust erosion detecting eye disorders
- constructing holograms from ordinary photographs
- diagnosing plasmas

At this time, however, neither NASA nor industry has been able to establish a clearcut commercial application competitive in cost and efficiency with alternative techniques. The first two NASA-supported activities, holography of microparticles and rocket engine holocameras, must be seen as research/development applications, since they permit the collection of information previously impossible to obtain. Although they have not yet been put to commercial use because of instrumentation limitations, this research did establish the feasibility of rocket and ballistic holocameras. The performance of the rocket engine holocamera has been improved and is now being further developed, independent of NASA support, to aid in pollution control, to perform wind tunnel and dust erosion tests, and to monitor rocket test stand operations.

NASA RESEARCH AND DEVELOPMENT

Holography of Microparticles

The effect of hypersonic impact or erosion of the reentry shield, shroud, or outer skin of space vehicles with clouds of micrometeorites is a critical aerospace problem, as is the erosion and possible damage caused by supersonic bombardment of aircraft panels and other structures by dust, dirt, or aerosol particles. Work is under way at the Langley Research Center (LRC) to simulate these effects by impact tests using artificial microparticles. To evaluate the tests properly, the density and size of the microparticles at impact must be very accurately known.

Although these particles may be photographed by pulsed laser light, this technique makes it impossible to determine their size accurately, and only a very narrow slice of the whole cloud can be focused in each photograph. If the exact position of the microparticle cloud is not known, coverage of dynamic events requires a whole battery of cameras, one camera for each slice making up the active test volume. Still the images cannot show accurate particle size and location. This problem can be solved with holography. One hologram can record the entire volume of the dynamic cloud of particles, and its reconstruction enables the exact size and three-dimensional position of each particle in the cloud to be measured.

LRC has recently been using inline holography to study the impact of tungsten and glass microparticles upon various types of structures. As shown by the diagram (fig. 6), only a single illuminating beam is required, and the hologram is formed by the interference between the plane illuminating wavefront and

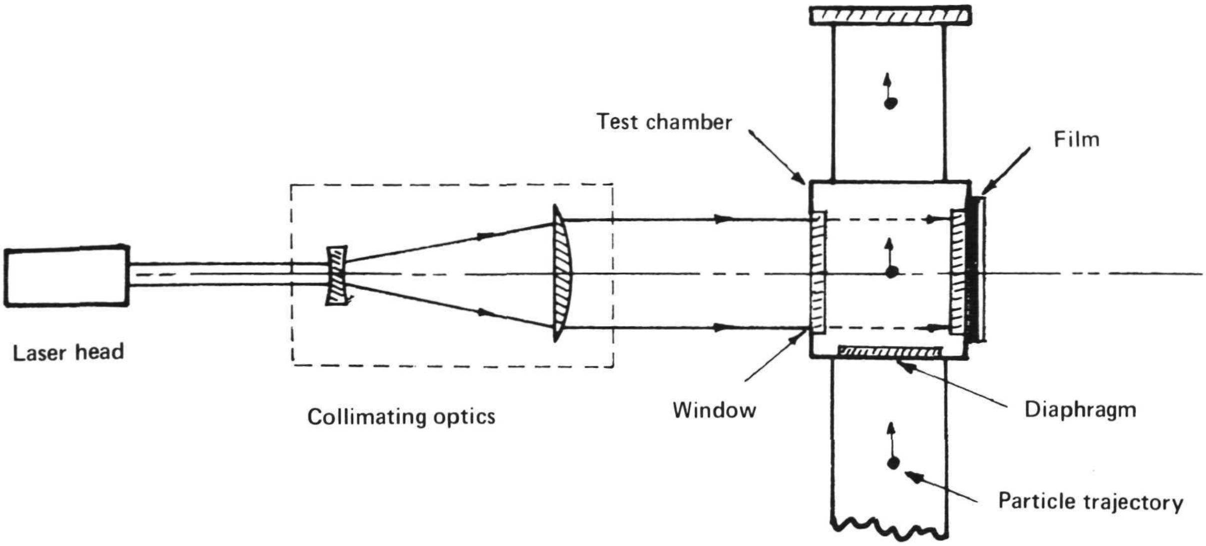


FIGURE 6.–Inline holography of microparticles.

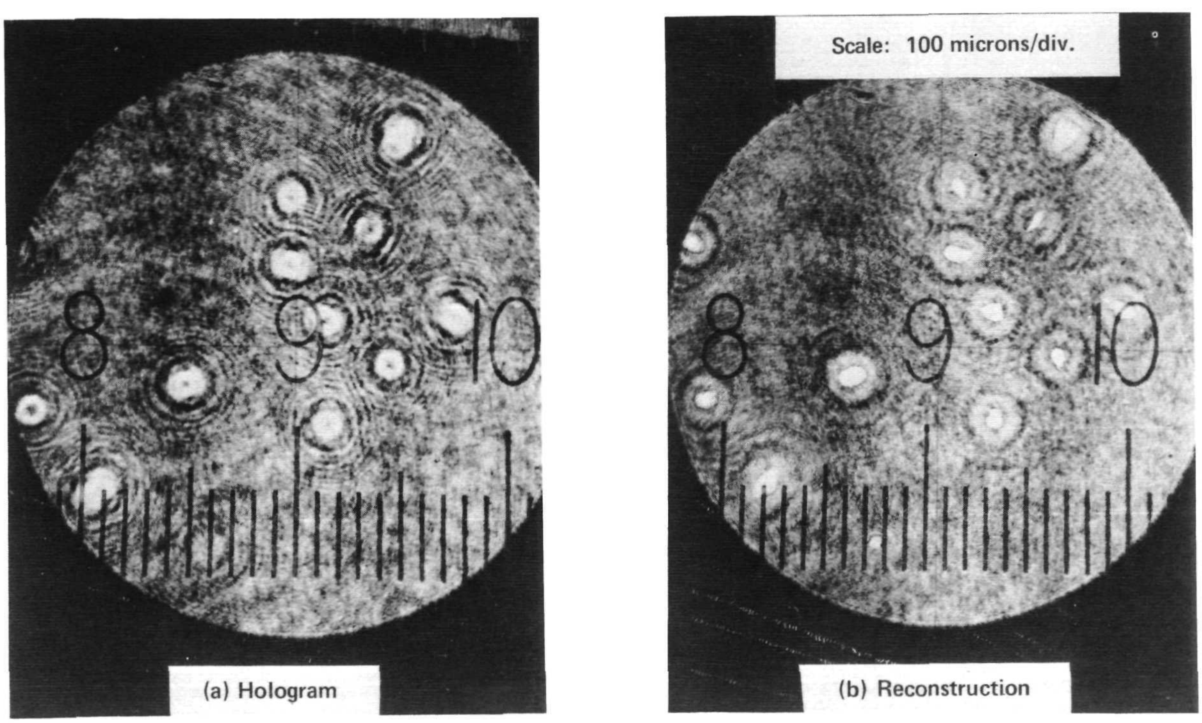


FIGURE 7.–Microparticle holograms and reconstruction.

the wavefronts scattered from each particle. The hologram is later reconstructed with a helium-neon laser (refs. 19 through 21).

Figure 7 shows both the hologram and its reconstruction. Since the hologram is a simultaneous recording of a number of microparticles at varying distances from the film, its reconstruction simultaneously forms the real three-dimensional images of all the particles in the cloud at their correct sizes and distances from each other and from the hologram. By

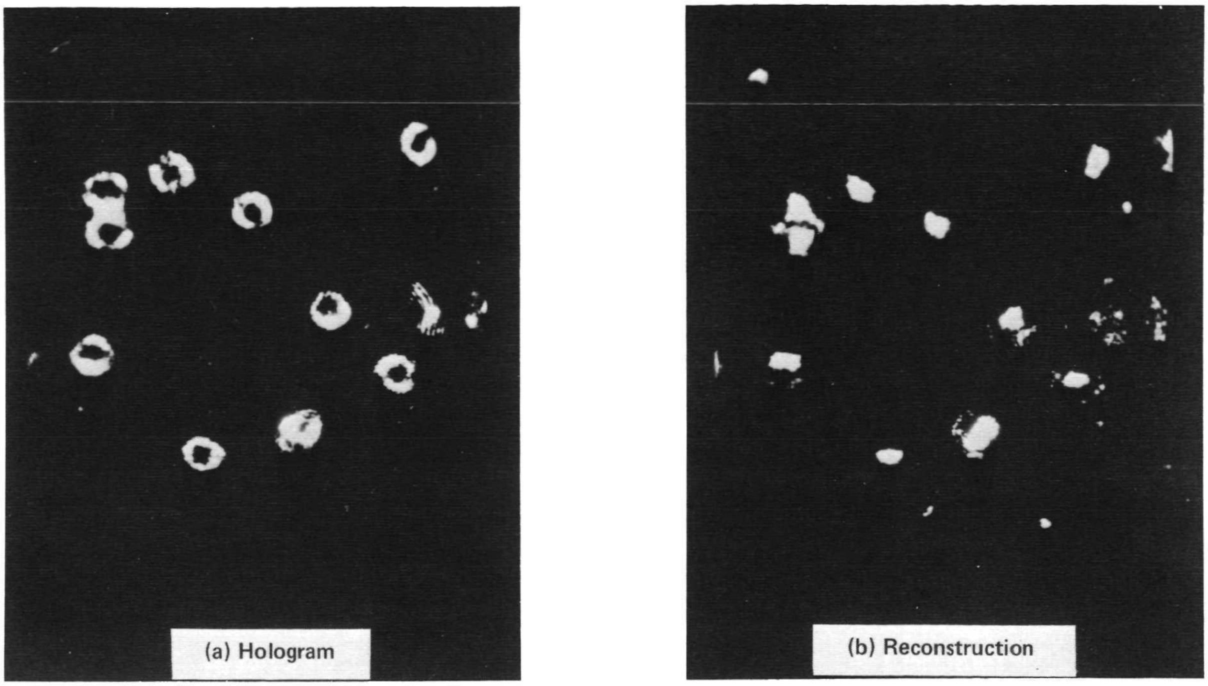


FIGURE 8.–TV holographic reconstruction.

using an auxiliary optical system during the reconstruction, successive planes of this image can be sequentially focused, magnified, and examined.

During the experiments at LRC, the real image planes were focused onto a TV camera and monitored on a TV viewing screen, greatly improving the contrast of the reconstructed image and making data reduction easier (refs. 22 and 23). This improvement is obvious in figure 8.

Rocket Holocamera Development

A team from Thompson-Ramo-Wooldridge, Inc. (TRW) Systems Group and JPL pioneered the development of rocket engine holocameras. Knowledge of the dynamic particle distributions of fuel and oxidizer during combustion is important for improving rocket propulsion systems and developing new propellants. The distribution of particle diameters and densities identifies problems connected with proper atomizing, mixing, and burning of the liquid and gaseous components in the rocket engines. Laser photography of these processes suffers from the same limitations noted above for microparticles. Even inline holography encounters severe problems due to the higher density of the reacting components and the high level of energy radiated by the combustion process. This high density of components causes great attenuation of the reference beam with respect to the scene and makes the proper ratio very difficult to achieve. Sideband holography in the holocamera reduced these problems.

The transmission mode holocamera, designed to work in the natural environment of the rocket engine test stand, has taken holograms of the combustion process of liquid rockets fueled with a number of different propellants. A photograph of the holocamera attached to the test rocket engine is shown in figure 9. The camera was remotely controlled from a blockhouse 500 feet from the test stand.

Best results were obtained during open flame tests, although some successful holograms were taken through windowed chambers. The holograms were recorded under the vibrational loads, thermal environment, and corrosive atmosphere encountered in typical rocket tests with earth storable propellants. The tests could detect individual droplets from records of preliminary cold water spray and reacting open flame spray, but only clusters of reacting components could be determined from holography of

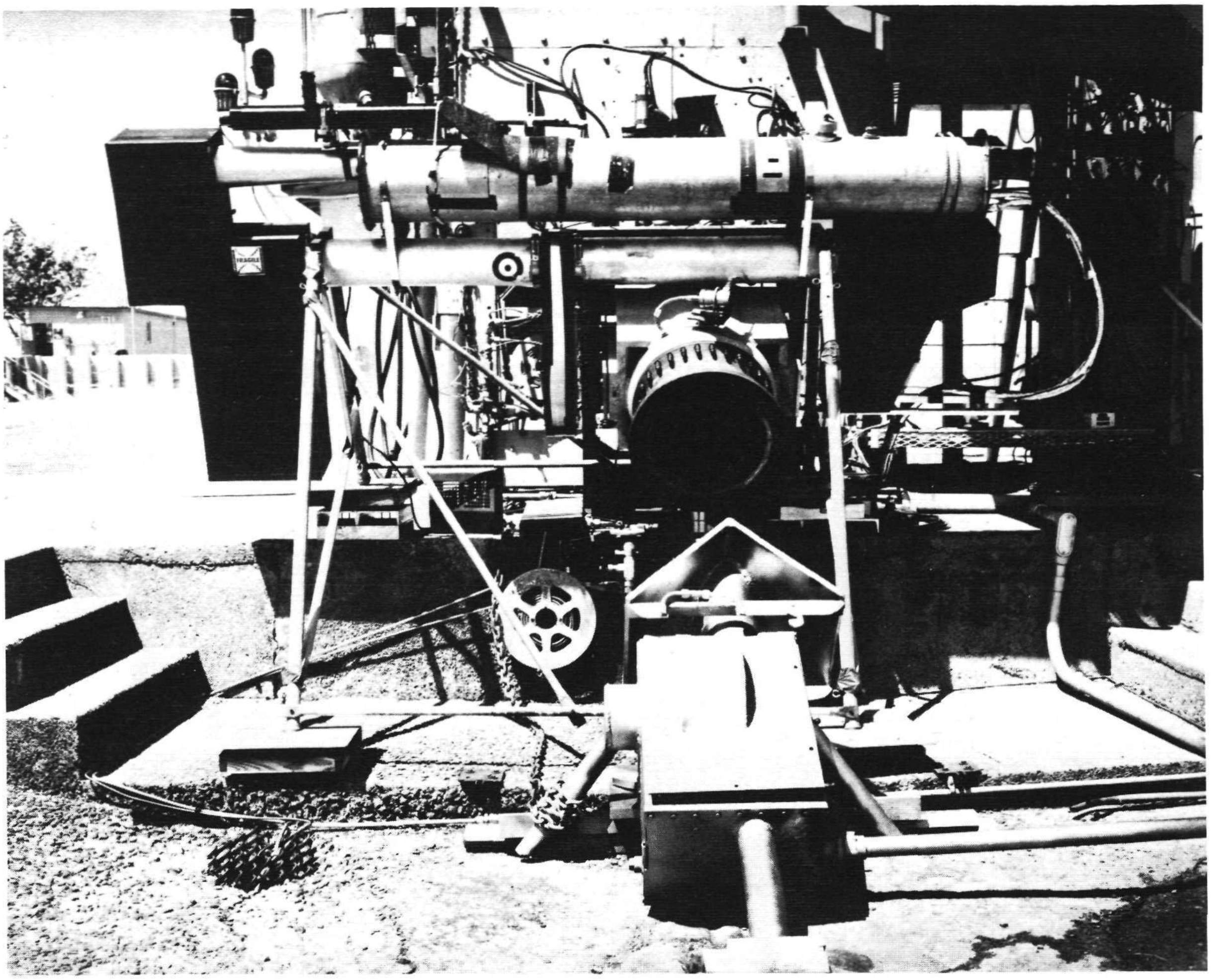


FIGURE 9.–Laser holocamera straddling 18-inch-diameter engine.

the confined combustion runs. The major problems encountered during these tests were engine starting roughness causing holocamera component accelerations as high as 30 g, heavy turbulence or convection of the combustion gases, and erosion of capped windows within the confined test chamber. The turbulence severely attenuated the laser scene beam (refs. 24 and 25). The holocamera schematic is shown in figure 10.

Reconstructed holophotographs of impinging cold spray and reacting hot spray during the cold flow and open flame tests were made. Figure 11 shows the open flame reconstructed hologram. The maximum resolution of the holocamera was 25 microns, but laser speckle limited the smallest observable droplet diameter to about 50 microns (refs. 26 through 28).

Improved pulsed ruby lasers with much longer coherence length are now available. These should alleviate some of the problems encountered in earlier tests and relax the stringent geometric matching requirements of the holocamera to achieve fine resolutions. However, the original contribution of this rocket holocamera to the technology of operating in the harsh vibrational, thermal, and internal absorptive environment of rocket test chambers has been clearly established.

Holography of Objects in Motion

NASA has been experimenting with a number of methods for obtaining holograms of objects in motion. Such holograms may eventually be useful in three-dimensional mapping of various types of dynamic and transient phenomena.

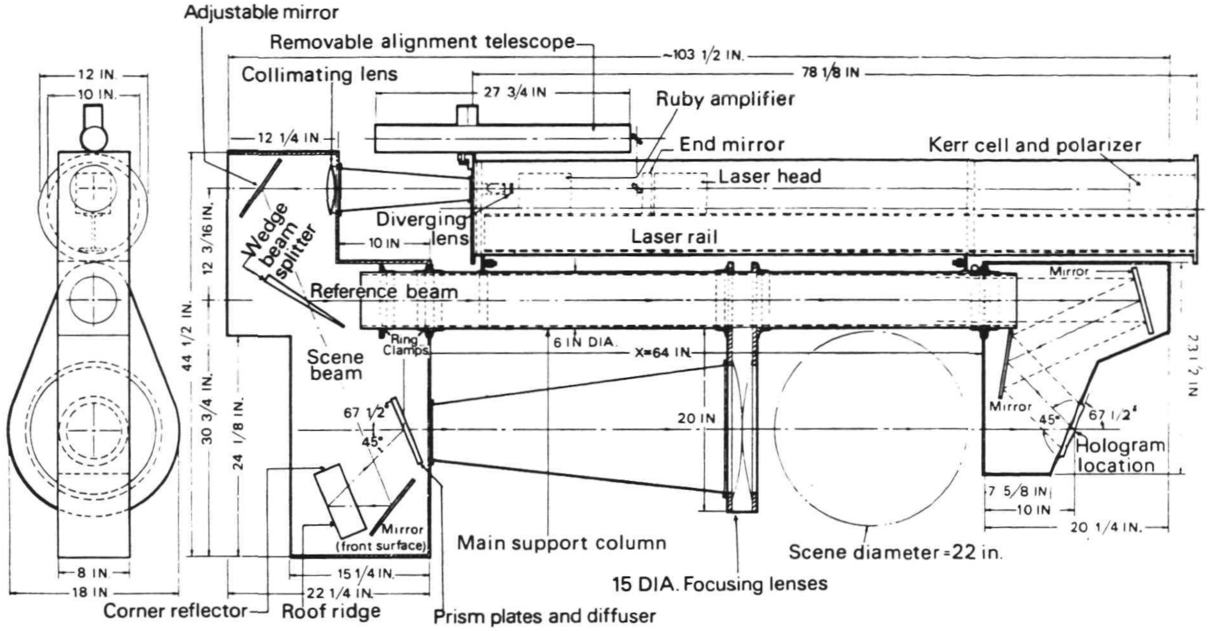


FIGURE 10.–Schematic of JPL pulsed ruby laser holocamera.

Several approaches have been tried. One series of experiments was based on the fact that the amplitude of the far field diffraction pattern of an object illuminated by coherent light will be invariant with the motion of the object, but that the phase of the pattern will vary with the object's position off axis and along the axis. This changing phase factor can be exactly compensated for by using the light intensity reflected from the moving object itself as the source for the reference beam (ref. 29). A second approach was to analyze the movement of the diffraction pattern fringes produced from normal inline holography, showing a correlation between the fringe movement and object velocity (ref. 30).

Both of these attempts encountered practical difficulties, but the most promising attack on the problem makes use of the geometric properties of an ellipse. If an illuminating source is positioned at one focus of an ellipse, a hologram plate at the other, and the object to be recorded moves along a tangent to the surface of the ellipse, the optical path length of the subject beam will be invariant during a short exposure. Therefore, the interference between the subject and reference beam will also be invariant, and stationary holographic fringes will be formed as reflected from the moving surface.

At the Marshall Space Flight Center (MSFC) this approach was tested experimentally to record pulsed ruby laser holograms of the surface of a rapidly spinning disk. Several modifications of the basic concept were devised during the tests. Figure 12 shows the experimental configuration using this concept; figure 13 is a photo of the experimental setup; and figure 14 shows a series of photographs of the reconstructed holograms taken at increasing velocities of the disk. Note that as the velocity increases, the maximum distance between points on the disk's surface to meet the required conditions of near invariance during exposure becomes smaller and smaller, as shown by the narrowing of the region over which a bright reconstruction occurs (refs. 31 through 33).

Aids to Practical Holography

NASA personnel at Ames Research Center (ARC), LRC, MSFC, and Goddard Space Flight Center (GSFC) have been active in developing new concepts and procedures to aid the setting up, recording, and processing of successful holograms.

H. Lackner of MSFC invented a scheme for checking the vibration level of the subject and the hologram plate fixture and its effect on blurring and wiping out the holographic interference fringes.

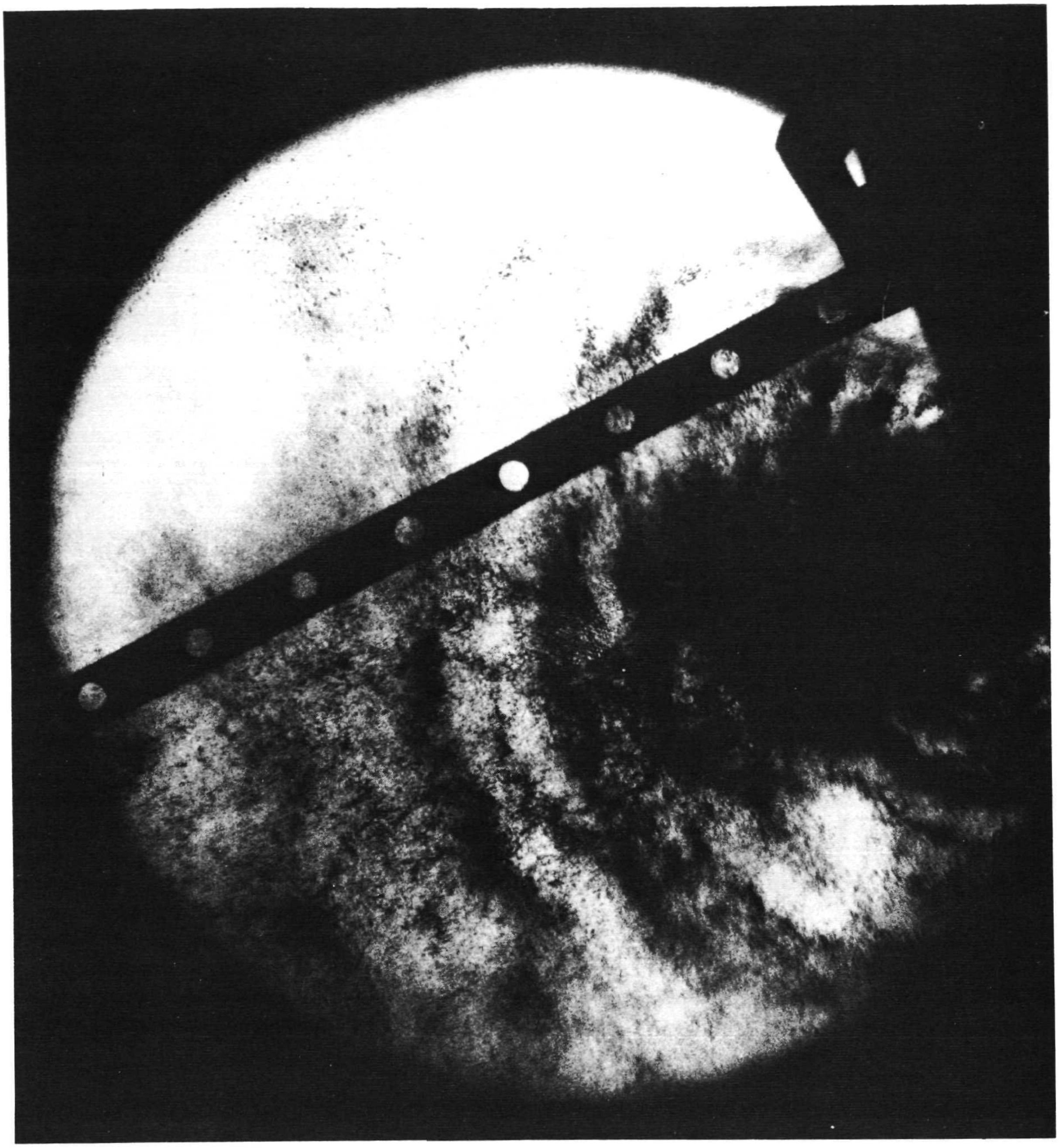


FIGURE 11.–Pulsed ruby laser reconstruction of hologram B1117G, recorded originally on 2-6-68 at JPL Edwards of N_2O_4–50/50 N_2H_4 UDMH propellant combustion. O/F = 1.25.

Excessive vibration of these elements is one of the chief pitfalls for the beginning holographer, and to date methods for diagnosing this problem have been complex and unwieldy.

The basic idea is to produce two sets of interference fringes, one set to monitor the vibrations of the object and the other set to monitor the combined vibrations of both the object and the holographic recording plate (ref. 34). Observation of these fringes before the hologram is exposed can ensure clean, high-contrast fringes (fig. 15).

R. Brown of ARC perfected a lossless method for

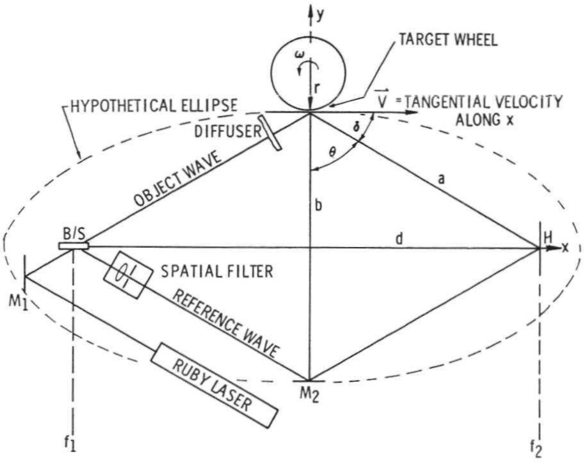


FIGURE 12.–Experimental ellipsoidal configuration.

varying the ratio between the signal beam and reference beam over eight orders of magnitude. It can also affect both the resolution and contrast of the exposed hologram and the diffraction efficiency of the reconstructed image (app. C). The usual methods of controlling the ratio by attenuation sometimes result in cutting the illumination level too low to make a good exposure.

The principle underlying this method is very simple (fig. 16). A Rochon prism divides the input beam into two perpendicularly plane-polarized components. Rotation of the half-wave plate about the optical axis rotates the polarization plane of the light incident to the prism. Since the horizontally polarized component of the light beam is passed straight through the prism while the vertical com-

FIGURE 13.–Ellipsoidal holographic system showing disc position.

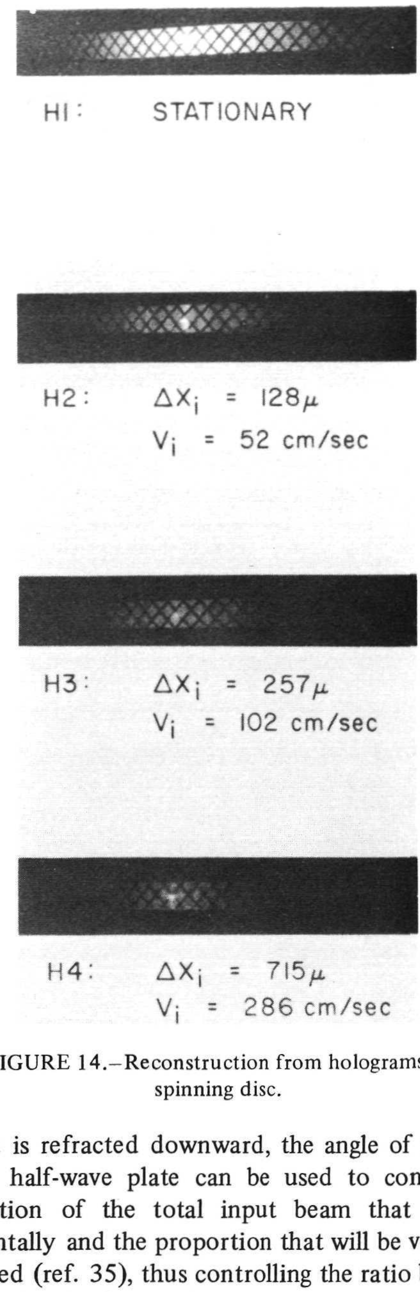


FIGURE 14.–Reconstruction from holograms of spinning disc.

ponent is refracted downward, the angle of rotation of the half-wave plate can be used to control the proportion of the total input beam that will be horizontally and the proportion that will be vertically polarized (ref. 35), thus controlling the ratio between the signal and reference beams.

An LRC working paper discusses significant factors in the basic equipment setup that affect hologram quality. These include the angle between the reference and object or scene beam; the intensity ratio between object and reference beams; seismic vibrations; acoustic vibration from air conditioners, fans, power supplies, etc.; laser stability for time averaged holograms, and room thermals. The paper also illustrates how an object permitted to move slightly during exposure may be invisible in the reconstructed hologram (ref. 36).

A more theoretical but lucid and practical treatment of holographic recording and processing can be found in the book *Optical Data Processing*, by A. R. Shulman of GSFC. The author assumes the reader has very little optical background, and sequentially describes the concepts of optics, photography, and mathematics necessary to understand holography and optical data processing. Discussions of experiments and theory are based on a number of fundamental investigations carried on for a year at GSFC laboratories (ref. 37).

COMMERCIAL ENDEAVORS

Several companies have developed complete consultation laboratories from which equipment and personnel can be leased to help a manufacturer apply holography to his requirements. A substantial number of completely engineered holographic systems are commercially available in a variety of sizes and have already been applied to many practical situations, ranging from plasma density studies in the physics laboratory to quality control inspection of production and R&D parts and components (refs. 38 through 44). (See also ch. 10.)

Furnace Holocamera

The TRW Systems Group has been investigating methods of applying holography to pollution problems for the Control Office of the Environmental Protection Agency. As a direct result of the experience gained in developing and operating the rocket engine holocamera, TRW instrumented a large cross-sectional area (24 by 48 feet) of a TVA coal-fired steam boiler with a holocamera working on a new two reference beam principle (fig. 17). Holograms were taken to evaluate different means of removing oxides of sulfur from stack gases of stationary power plants.

These oxides contribute heavily to atmospheric pollution if they are not completely removed by a complex process combining chemical combustion and electrical precipitation. The efficiency of this process depends upon the uniformity and coverage of clouds of pulverized dry limestone periodically blown into the furnace. The holocamera can analyze the penetration, dispersion, and continuity of this limestone

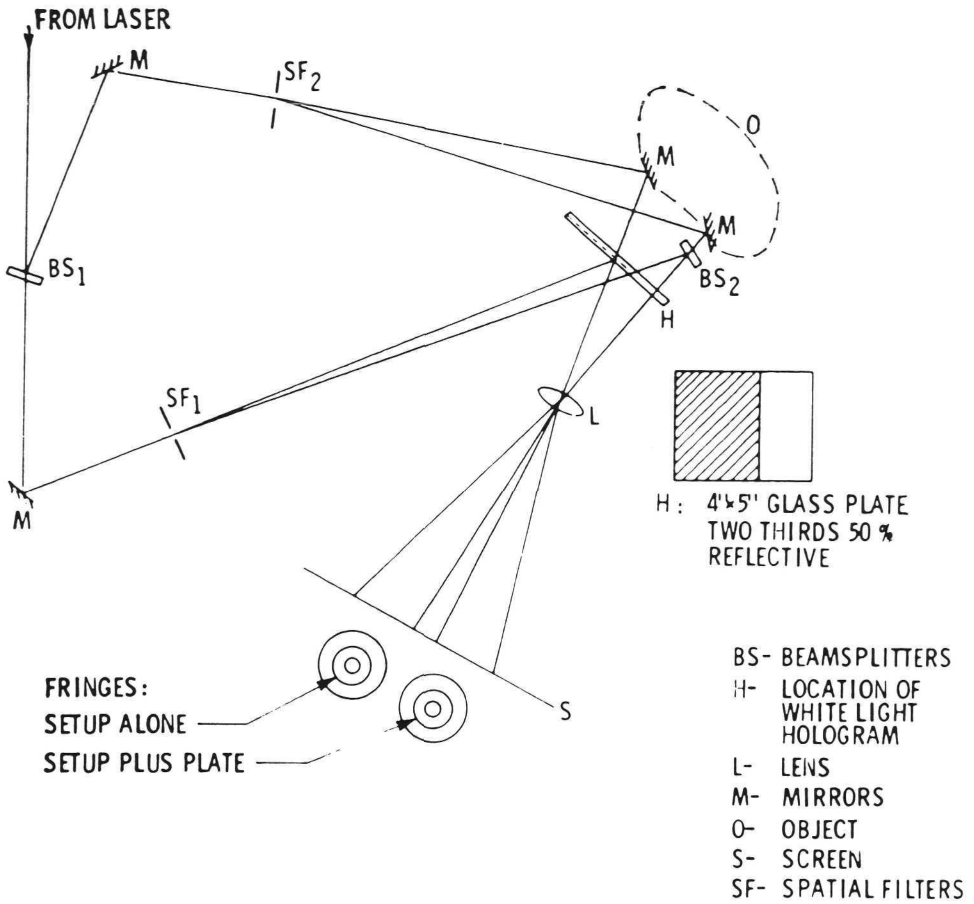


FIGURE 15.–Holographic vibration test setup.

cloud by measuring the density distributions of particles at different parts of the furnace. TRW is also making holographic studies of the operation of domestic home furnaces for pollution control purposes (refs. 45 and 46).

Reacting Spray and Dust Holography

Interesting applications of holography are also being developed at the Arnold Research Organization, Inc. (ARO). R. A. Belz, J. D. Trolinger, and coworkers have obtained holograms of reacting liquid spray droplets down to 15 microns diameter using an inline holocamera mounted on a rocket test stand.

Inline holography has also been used at ARO to make coherent shadowgrams in a hypersonic dust erosion facility to record explosions, plasmas, and engine exhausts in wind tunnels. These holograms can give information about flow fields, particulate contents, and fluid effects. In addition, ARO personnel have made data reductions based on theoretical diffraction studies involving inline holograms of projectiles in flight (refs. 47 through 49).

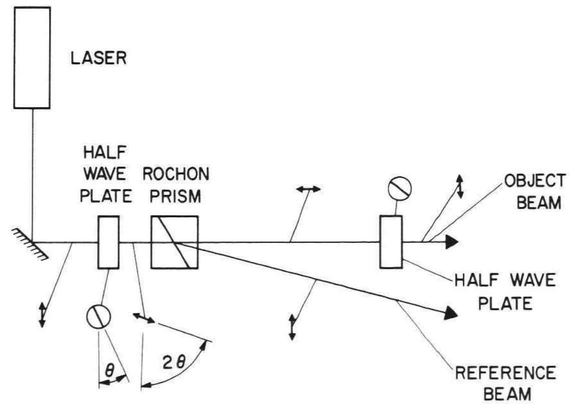


FIGURE 16.–Variable ratio beam splitter.

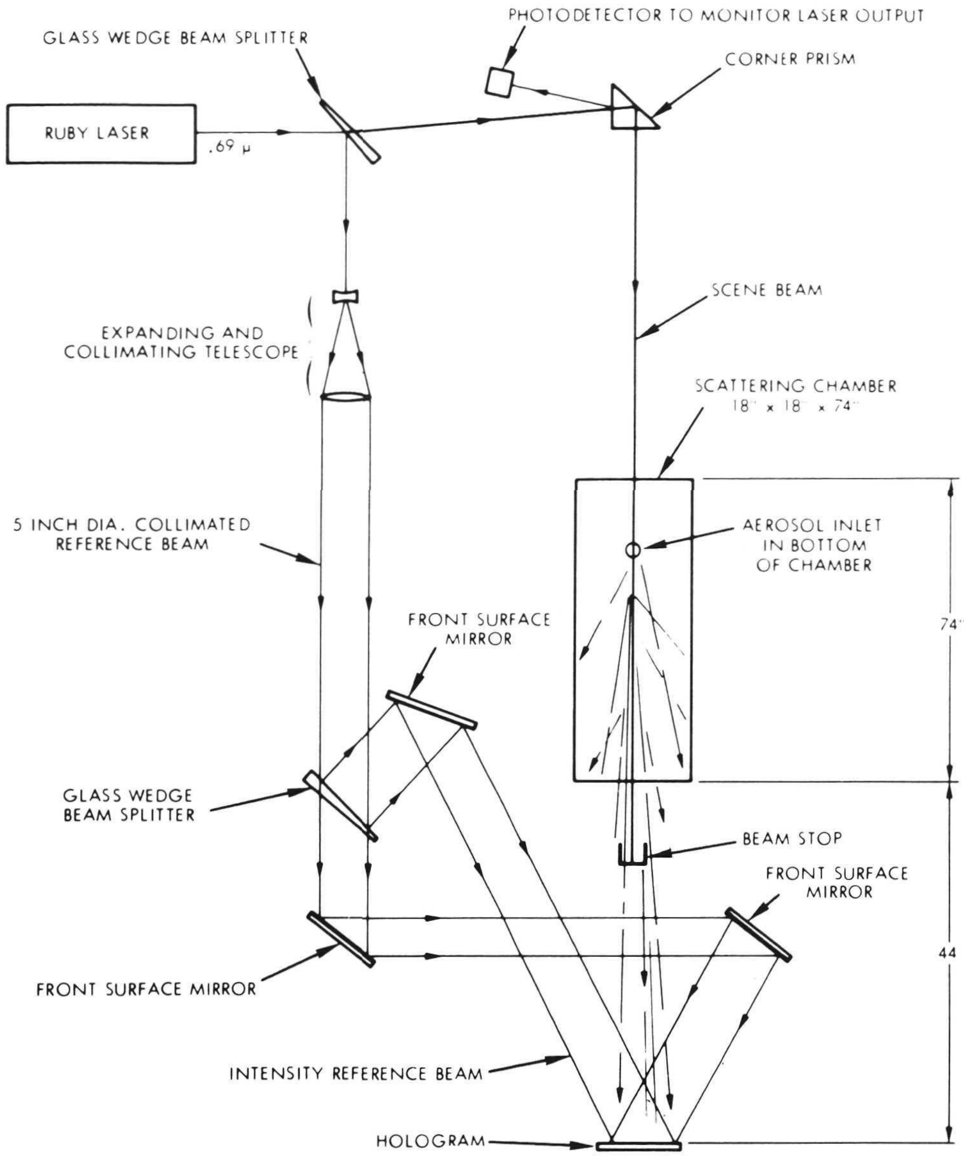


FIGURE 17.–Schematic of scattered light 3-beam transmission holocamera test setup.

Eye disorders may soon be discovered in earlier stages to make treatment easier and increase the chance of cure. A number of researchers have been experimenting with three-dimensional holographic images of human and animal eyes. These methods have enabled the detection of glaucoma and other such ailments even in the presence of cataracts. Holography can record the innermost layer of the back part of the eyeball for later analysis, as well as nearer layers along the optical path (ref. 50).

Thanks to a new procedure, holograms can be made using only a series of photographs taken by a camera in ordinary illumination. This technique simplifies holography of objects at substantial distances from the camera. It is a three-step process. First, a montage of ordinary photographs is made from a variety of aspect angles; second, these are recorded in a special way on a hologram using coherent light; and, third, the hologram is illuminated to reconstruct the three-dimensional image. The process does not work when precise holograms are required, such as those needed in holographic interferometry (ref. 51).

Holographic techniques have also been applied to

such diverse problems as determining the density profile in a laser-created plasma, examining the bubble spectrum in a cavity tunnel, studying the optical properties of atmospheric aerosols, measuring liquid droplets in carburetors, studying laser velocimetry, and analyzing electron-beam induced front surface effects. Incoherent holography has been used to photograph the stars. Keuffel and Esser Company reported a holographic method for monitoring the performance of large mirrors; and *Laser Focus* has described an ingenious holographic art studio using boxes of sand as mounts rather than expensive slabs of granite (refs. 52 through 60).

THE FUTURE

Holographic Diagnostics and Measurements

Many industrial problems associated with the behavior of mil-sized particles, droplets, spray, or moving parts may be amenable to holographic diagnostics and measurements. These industrial applications usually involve processes of relatively low velocity in near normal atmospheres, and can probably be handled by current holographic devices. Measurement, monitoring, and mapping of the size distribution, particle densities, and particle density isobars in volumes and planes of space appear feasible for all types of aerosol, spray, and particle concentrations. The use of more sophisticated two- and three-beam holocameras like those developed for pollution control studies will probably allow examination and measurement of the internal functioning of gasoline engines, carburetors, rocket chambers, fuel combustion, and chemical and nuclear reaction chambers. Dye lasers that can be tuned to minimum absorption wavelengths of the reacting gases and combustion products should be investigated as illumination sources.

Because of the advances in holography, processes such as combustion, burning, explosion, carburetion, exhaust, emission, impact, braking, erosion, seeding, catalysis, mixing, dispersion, and diffusion will be observed and controlled more efficiently than ever before. The potential in this field is enormous, ranging from pollution control to the design and production of better aerosol containers that will provide finer, more evenly distributed sprays of insecticide, paint, and deodorizer.

Recording Materials

NASA and its contractors have developed a number of techniques and devices to aid industrial concerns embarking into new areas. Among these are high velocity recording materials and practical aids for recording holograms.

One of the practical problems in producing good holograms is to learn how such things as hologram exposure levels, reference-to-scene-beam ratio, exposure time, type of recording medium, and other considerations will affect the diffraction efficiency, contrast ratio, and resolution of the reconstructed hologram. At present there are no standardized holographic curves of performance. Scientists and engineers at MSFC have recently begun an ambitious series of controlled experiments and precision laboratory measurements aimed at filling this gap.

The University of Michigan has also been under NASA contract for some time to develop techniques for improving the diffraction efficiency of holograms. Bleaching of silver images has been successful in producing phase hologram diffraction efficiencies of 60 to 70 percent. Photochromics have also been studied because of their potential for real-time processing by exposure to radiation of the proper wavelength. They also show promise for development of erasable holograms because of their reversible characteristics. However, since they produce only amplitude holograms they are limited to about a 4-percent maximum diffraction efficiency (refs. 61 and 62).

NASA contractors and many individuals and research groups are exploring new materials that promise real-time and erasable characteristics. Hughes Research Laboratory has developed photopolymer materials for phase holograms exhibiting very rapid development time, moderate sensitivity, diffraction efficiencies up to 45 percent, and resolutions up to 1500 line pairs per millimeter. Bell Telephone Laboratories (BTL) has been concentrating on dichromated gelatin for the same purposes. Neither of these phase hologram materials is erasable, but erasable photochromic materials being developed by Radio Corporation of America and the Soviet Union typically have low diffraction efficiencies (refs. 63 and 64).

The prospect of erasable phase holograms with high diffraction efficiency is being explored by BTL, Sperry Rand Research Center, Texas Instruments, Xerox, RCA, Honeywell, and International Business

Machines researchers. Materials such as ferroelectric barium titanate and lithium niobate crystals, thermoplastic or elastomer film sandwiches, and thin ferromagnetic films are currently under investigation (ref. 64). One of the most promising is the arsenic trisulfide film discovered at RCA which can be visually observed during real-time dry development using light (ref. 65).

Several researchers have made successful holograms with infrared energy. F. M. Shofmer of Environmental Systems Company used conventional Kodak IR film 2481 to make inline holograms (ref. 66). Ling-Temco-Vought, Inc. (LTV), used a thermochromic crystalline type material, while the Japanese are experimenting with photochromic films and liquid crystal area detectors to record infrared holograms at the 10.6-micrometer wavelength. Before reconstruction can take place, the thermo-image on the detector must be recorded on ordinary film (refs. 67 through 69).

CHAPTER 4

Holographic Display

The earliest application of holography was the display of amazingly realistic three-dimensional images. Yet in many ways, the display aspect of holography has not kept pace with more esoteric applications. NASA has done a limited amount of work in the field, and some other government and private organizations have also made contributions.

Holographic displays generally fall into two groups: (1) those where the three-dimensional image may be viewed directly, as in advertising displays, and (2) those where the image is picked up by a TV camera for two-dimensional display. This chapter discusses mainly single-exposure presentations of recorded holograms. Multiple exposures or fast time sequences are covered more fully in chapter 7, and holographic display devices developed for presentation of acoustic holograms are described in chapter 8.

NASA and its contractors have formulated display concepts for training, for status and situation presentations, and for special effects. They have also proposed ideas for hologram displays using extended illumination sources and synthetic point generators. Some effort has been made to produce large three-dimensional displays for advertising, engineering, scientific, and entertainment purposes. Several of these devices can present color images largely free of the objectionable laser speckle effect, while others are designed to help evaluate the complex holographic interference patterns produced by inline holography or holographic interferometry. With DOD support, several separate schemes are being pursued for development of a flight simulator and synthetic three-dimensional displays for air traffic control, status and readiness, and other aircraft requirements.

Only the large three-dimensional display systems and the smaller portable systems may be considered commercially useful. Marketable and profitable exploitation of these display systems cannot be evaluated yet, since it is difficult to estimate the cost of using holography in design, architecture, advertising, and other commercial areas, and to compare the cost with that of more conventional techniques.

NASA RESEARCH AND DEVELOPMENT

As early as 1967-68, NASA sponsored a study of how holographic displays could serve as training aids, cockpit displays, and static displays. This study developed the concept for a system to train an astronaut by simulating the approach to a target vehicle during a rendezvous maneuver.

To achieve realism in such displays, it is critical to simulate as closely as possible the angular size of the target and its apparent approach distance and velocity. So far the best ways devised to create the three-dimensional effect are by stereo movies or holography. The main drawback of stereo movies is their lack of flexibility in the angle of approach; the observer is also required to wear special glasses or filters that are annoying. University of Michigan, the NASA contractor, discovered that by moving the distance and the angle of a point reconstruction source from the illuminated hologram, the apparent distance from the observer and the orientation of the target vehicle could be changed. This analysis, based on sound holographic theory, derived an exact expression for the apparent size and velocity of the simulated target as it moved toward the observer. This was then compared with the real target's size and velocity.

One tentative concept for reconstructing and viewing the virtual holographic image is shown in figure 18. The hologram is the "window" for the observer. This approach was discarded because the apparent angular magnification of the virtual image failed to match the actual situation. The problem was solved by using a simulation system based on reconstruction of the real holographic image. This more

534-778 O-74—3

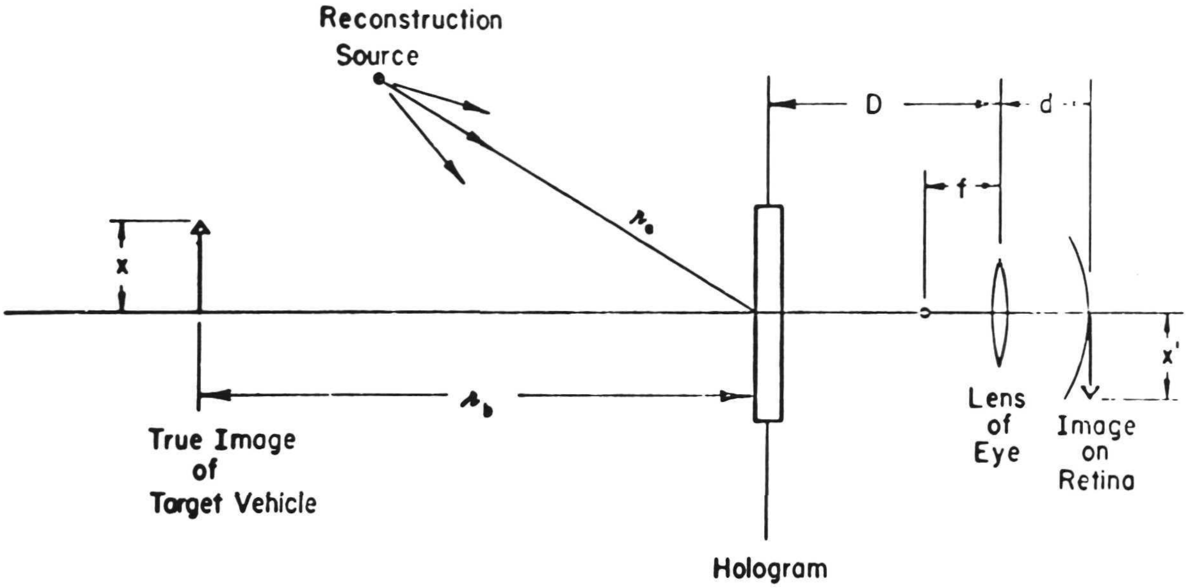


FIGURE 18.–Simulating spacecraft rendezvous by holography.

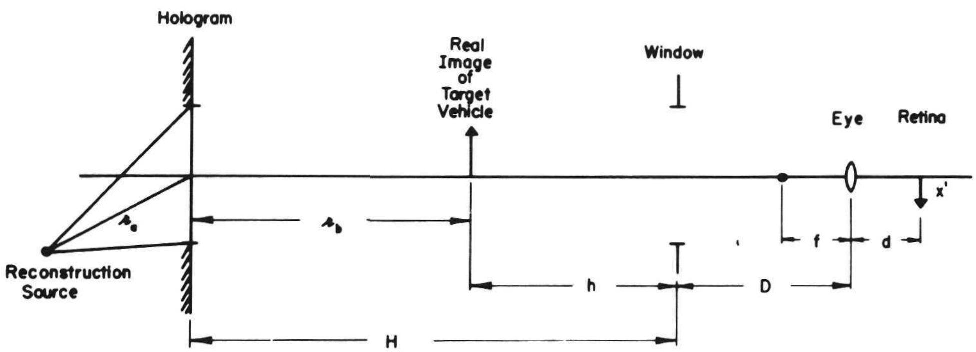


FIGURE 19.–Geometry for observing the real image of a hologram in a spacecraft rendezvous problem.

complex system requires a separate window aperture as well as the hologram (fig. 19). The apparent approach velocity of the target is the most critical factor and must equal the velocity of the real target at all ranges. Movement of the angle of the reconstructing source point can simulate an angular rotation of the target; it is governed by the thickness of the hologram emulsion. Using a standard thick hologram, the target can be rotated a maximum of about 10 degrees before the image is extinguished.

A second novel idea advanced during this study was to holographically simulate a cockpit display for testing navigation aids. The basic idea was to reconstruct a number of higher diffraction order points upon illumination instead of the nominal first order. This series of reconstructed points can be made to appear as a set of straight lines converging near the top of the display, thus simulating the appearance of perspective.

Although holography is popularly called lensless photography, the basic holographic equipment is usually augmented with lenses to magnify the reconstructed image or to increase the field of view (ch. 5). At the Electronic Research Center (ERC) a method was invented that permits a less precise match between the reference illumination used for reconstruction and display and the one needed to record the hologram. The two patent applications related to

this invention claim that "the same or a different coherent extended source, a point coherent source can be used" during the reconstruction. Moreover the "hologram or reference source misalignment is not critical," and the real image reconstructed is nonpseudoscopic (not distorted inside-out) as is normally the case (ref. 75).

The basic idea of this invention is quite simple (figs. 20a through 20c). Instead of making a hologram of an object either by reflection or transmission of scattered energy, as in the conventional method, a hologram is made by exposing the plate to the real image (aerial) of the object. This image is projected onto the hologram plate by means of a large aperture, high quality lens (*L* in the figure). Such an arrangement permits the image to be formed immediately in front of the plate (fig. 20a), to straddle the plate (fig. 20c), or to project out beyond the plate (fig. 20b). All of these configurations may be used, depending upon the display effect desired. The feature of producing the real image very close to the plate, according to the inventor, L. Rosen, allows relaxation of precise positioning and alignment conditions on the diffuse source used for the reconstruction. The major obstacle is the need for high quality, large aperture lenses (about 5 in. in diameter) to form the holograms (refs. 75 and 76).

COMMERCIAL ENDEAVORS

Commercial Displays

A commercial holographic display at the opening of General Motors' International Building was set up in an octagonal case with four "windows" that were actually holograms, each containing two different scenes. The visible scene was governed by the illumination angle of the laser beams; each of the four windows contained different views of the same scene, so that by walking around the display case one would have a full 360-degree view. One scene showed a Napoleonic coach and the other an auto body. For added impact, the interior of the case was periodically illuminated with diffused light to show that the case was empty. A single source of illumination was used for the four 1-1/2 by 2 ft holograms (refs. 77 and 78).

Developmental work on large holographic displays is being pursued by a number of corporations, and small displays are already on the market. A unit the size of an attaché case (4 by 14 by 18 in.) and weighing only 13 lb is available for $250. Color is being introduced into displays by using multiple lasers. One system uses a krypton laser to obtain red and an argon laser to obtain blue and green, producing a full color hologram. A number of combined recording and display systems that make 4 by 5 in. holograms and their reconstructions using conventional spectroscopic plates are also on the market (refs. 79 through 83).

An information processor and display system is available that analyzes inline holograms in the 10- to 1000-micrometer range and then displays the reconstructed sample volume. The positions of the video camera and imaging lens can be continuously varied by the operator to allow accurate focusing and sizing of the particles (ref. 84).

Another company is experimenting with color displays in conjunction with a rear projection screen. The use of photoluminescent dyes in an array of red-blue-green dots, interacting with the properties of a nematic-liquid crystal screen for the laser display, can increase contrast and resolution as well as reduce speckle and scintillation. These screens are being developed to view microholograms at the output end of a high-capacity data storage and retrieval system (ch. 9) (refs. 85 and 86).

Dynamic Displays

A dynamic display system is also under development to produce synthetic real images. These three-dimensional images are formed holographically from input coordinate data, ideal for situation or readiness displays. The display is built up in three-dimensional space from a series of dots sequentially formed at a rate rapid enough for the eye to see all the dots corresponding to a frame time superimposed in space. Each dot is formed holographically by the interference between a displaced object point source and a reference point source. This innovation is based on the principle that displacing the object point source in the depth direction can be simulated by displacing the reference point source. A feasibility model for a quasi-real-time system is currently being constructed. The system requires several seconds for development between frames (refs. 87 and 88).

Perhaps the greatest problem with most flight simulators is the difficulty of showing the pilot a realistic image. Many simulators use motion picture

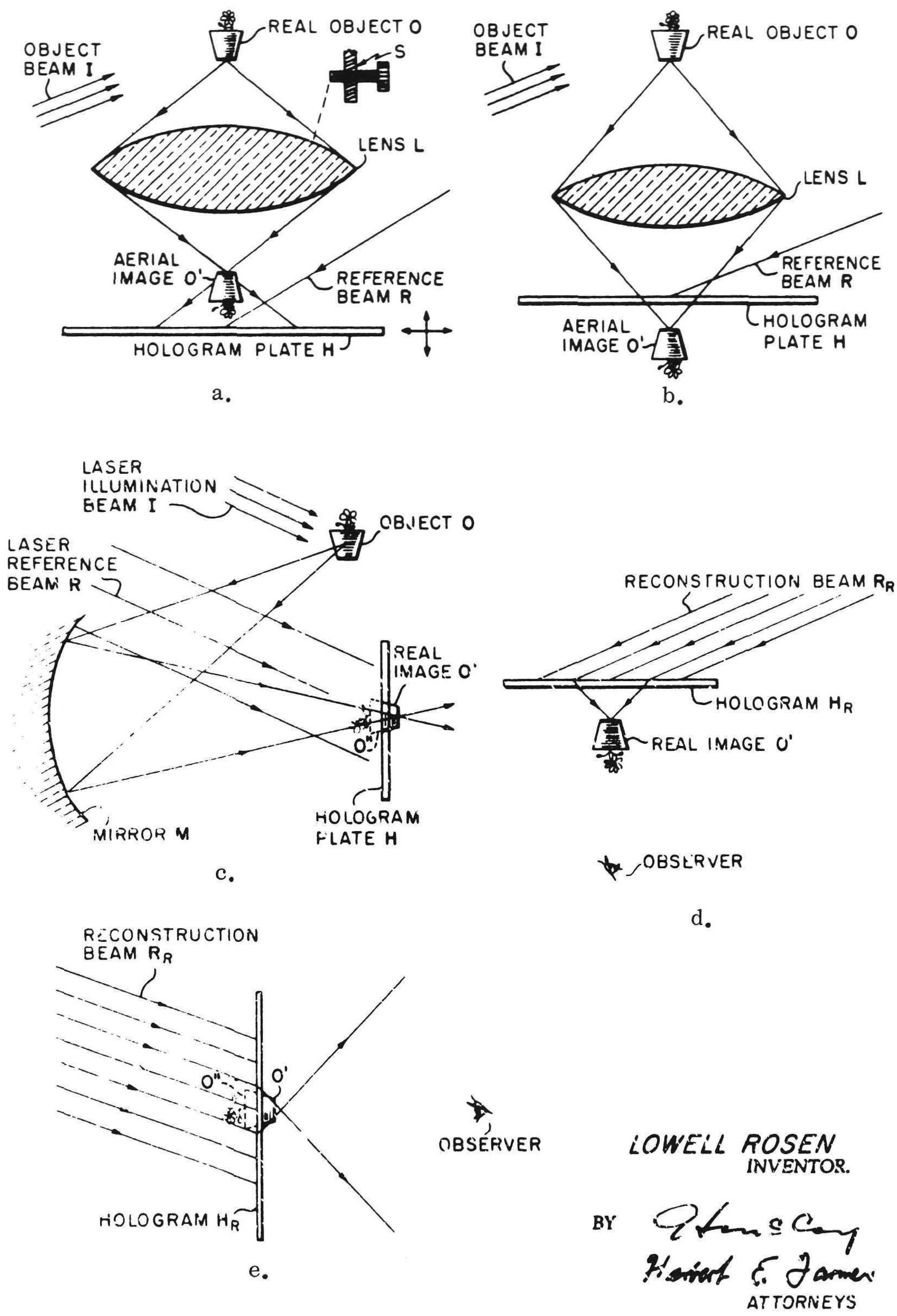


FIGURE 20.–Recording and reconstructing focused image holograms.

film or TV screens, but these techniques cannot compactly produce a continuously varying three-dimensional illusion. DOD is supporting development of an airborne holographic headsup display system which could assist the landing of an aircraft on board a carrier either at night or when normal visibility is blanked out (fig. 21). The simulator is configured as follows. First a hologram is made of an aircraft carrier model. After processing, the hologram is illuminated by a laser, and its image magnified by a lens to recreate a full three-dimensional presentation at normal viewing range. To depict varying approaches and pitch and roll maneuvers, a gimbal and linear drive system has been devised to link the TV camera and the hologram. As a result, the picture on the display TV is both angularly and spatially correct at the start of the simulation and also continuously varies as the approach is made exactly responding to the controls imposed by the student pilots (refs. 89 and 90).

One of the largest electronic manufacturers is developing a holographic system for displaying taped video programs on home color TV sets. Cost is currently the primary obstacle in providing the video tape to the individual viewer. Scanning conventional color film appears prohibitively expensive, and the use of video magnetic tape, although less expensive, does not seem amenable to a high enough data storage density. The "Selectravision" concept may be the answer. In this system, a two-dimensional TV display is generated by scanning a reconstructed image formed from a relief phase hologram.

The process begins with conventional black and white filming of a color scene. However, the color signal information is superimposed upon the film in

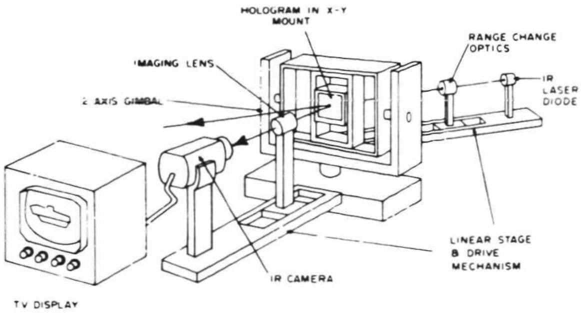


FIGURE 21.–Feasibility model of holographic flight simulator

vertical stripes that are almost invisible. Subsequently the processed film is illuminated with the object beam of a laser and, in combination with the reference beam, a relief hologram is made on specially prepared tape. After appropriate processing, this tape becomes the master that can be inexpensively reproduced on the embossed tapes used in individual cartridges. The compact player, designed to sell for about $400, consists of a low power helium-neon laser, a tape drive system, a small Vidicon TV camera, and appropriate electronics.

For home viewing, the laser illuminates the hologram frames. The black and white picture is picked up by the Vidicon, and the color information is stripped off the video signal to provide regular color TV signals for display on the home set. The use of embossed vinyl hologram tapes, in addition to providing movies at about $3 a program, has the advantage of being far more resistant to scratches, abrasions, and imperfections than ordinary film or magnetic tape (refs. 91 and 92).

CHAPTER 5

Holographic Microscopy

Microscopy, the application for which Gabor invented holography, can benefit significantly from holographic techniques. Two forms of holographic microscopy have been developed, one using holography in conjunction with ordinary microscopy and another using the magnifying properties of holograms, usually with auxiliary beam-forming optics. Since biological and physical scientists make extensive use of microscopy, it is only natural that their findings have been greatly enhanced by this new technology. Holography's greatest contribution to microscopy is its ability to freeze in three dimensions a transient event occurring on a slide, thus allowing further examination or interferometric comparison with similar events later.

One of the interesting current applications of the commercial holographic microscope is the study of dynamic events such as crystallite and biological growth and bacteria movement, a critical area of medical research. Another is holographic projection of images to assist in the manufacture of more reliable, less expensive, integrated circuits and microelectronic components.

The earliest method of holographic microscopy—the one Gabor intended to use—was to obtain magnification by reconstructing the hologram with a longer wavelength than that of the original recording. The degree of magnification would equal the ratio of the reconstruction to the recording wavelength.

A purely geometric "lensless" approach investigated by E. Leith obtained magnification by decreasing the radius of curvature of the reference reconstruction beam as compared to the recording beam (fig. 22a). As can be seen, no optical element is placed between the object and the hologram, hence the designation "lensless." In this type of microscopy, relatively uncorrected lenses, like those shown in the diagram, are used to generate divergent spherical waves for object and reference beam illumination. The processed, reconstructed real image can then be examined at a variety of magnifications under a conventional microscope. The major problems in this approach are the presence of image aberrations and the relatively small factor of magnification possible (~100); great care must also be exercised to avoid film shrinkage and distortion (refs. 93 through 95).

The most practical approach developed so far is called the "corrected optics approach," in which

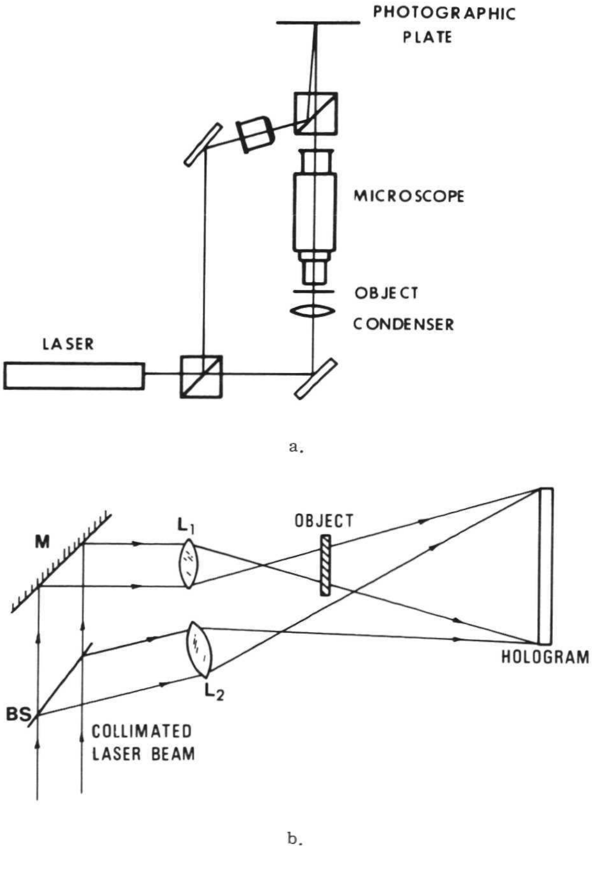


FIGURE 22.–Holograph microscopy approaches.

PRECEDING PAGE BLANK NOT FILMED

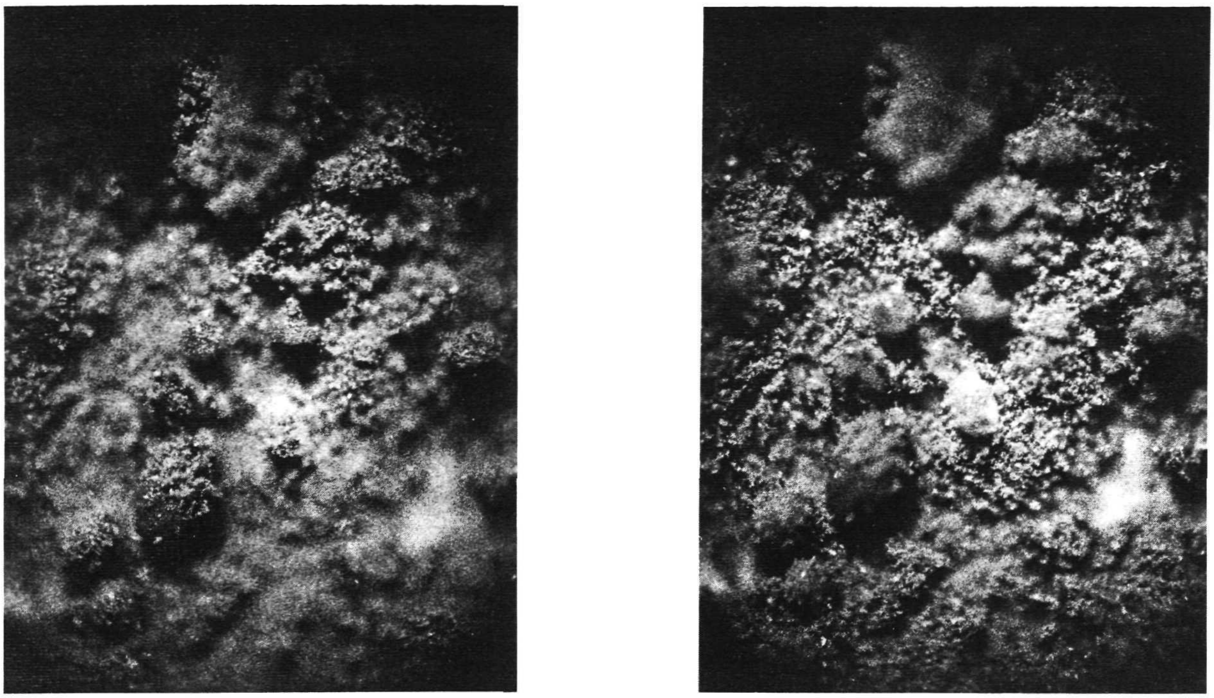


FIGURE 23.–Holographic image of simulated lunar surface at 32X. (The left photograph is focused approximately 0.2 mm deeper into the surface layer than the right photograph.)

holography is used in conjunction with ordinary microscopy. This method, introduced by R. F. van Ligten, requires finely corrected microscope optics between the object and the hologram (fig. 22b). As a result, the hologram does not require magnification upon reconstruction. The drawbacks of this method are that the field of view at the hologram plate is reduced by the microscope optics in an amount inversely proportional to the square of the magnification; and the depth of field is limited by the *f* number (ratio of focal length to diameter) of the correction optics. Resolution on the order of 1 μm is possible using this system; it is the basis for the NASA work supporting the testing of integrated circuits reported below (ref. 96).

NASA RESEARCH AND DEVELOPMENT

Holography of Integrated Circuits

In a study performed for ERC, R. F. van Ligten investigated the application of holographic microscopy to nondestructive testing of monolithic circuits. The two prime conclusions reached by this study were:

1. The holographic phenomenon of wave front storage is applicable to microscopic failure detection when the appropriate correlation between electric and optical behavior is established.
2. Interference effects produced by integrated circuit components (i.e., silicon wafers) in the invisible infrared may be stored in holograms for later visible reconstruction and diagnosis.

On the basis of these observations, van Ligten proposed that a microscopic hologram be made of an integrated circuit at various stages during the manufacturing process. Electrical checkout of the unit at the end, or at intermediate steps, would allow correlation of the electrical properties with the appearance of the optical hologram. In this way, a baseline or reference set of holograms could be established. Viewing subsequent sample holograms interferometrically over the reference holograms would then show flaws in the unit at any stage in the process. Deviations in parameters such as depth of

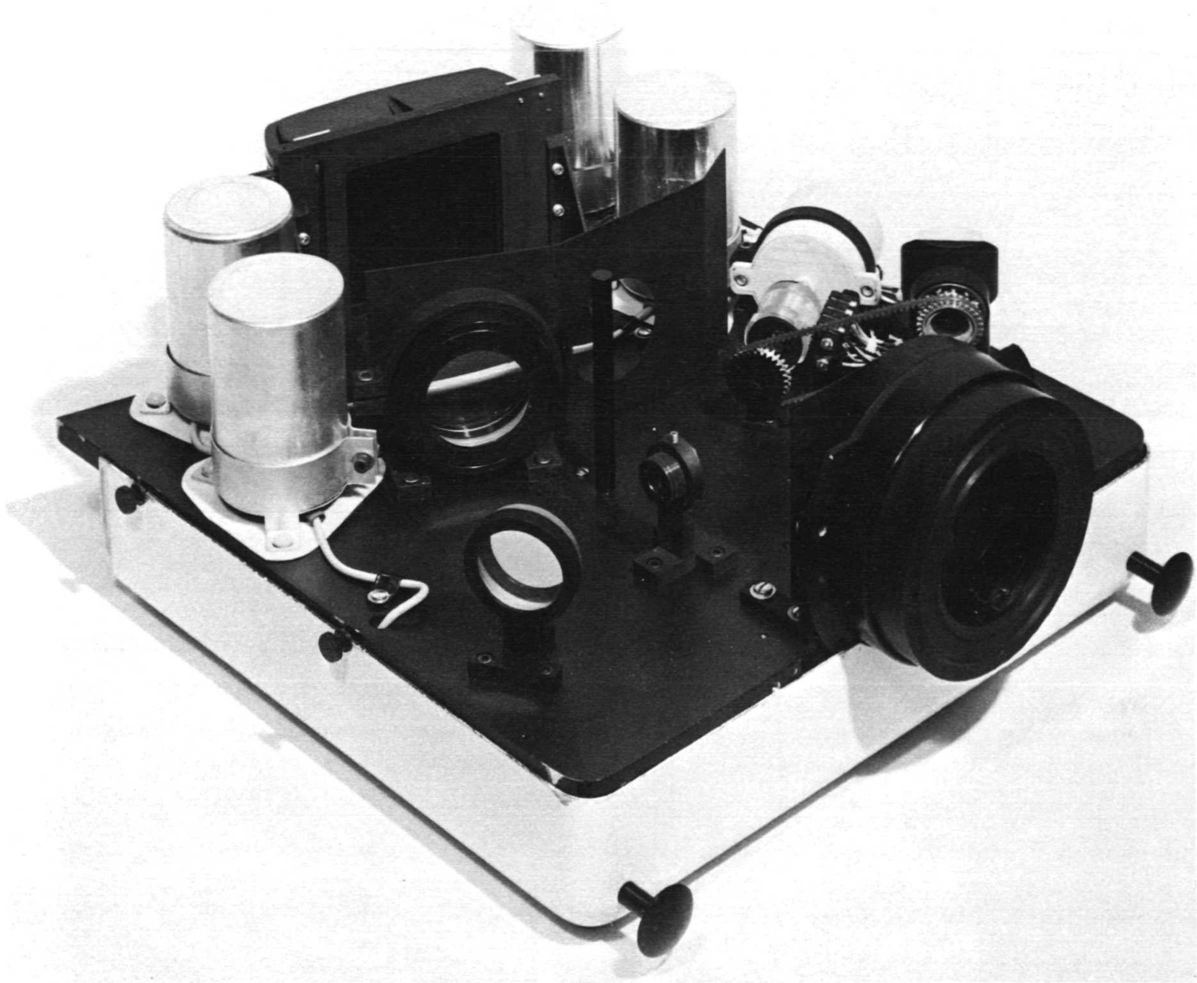


FIGURE 24.–Prototype holocamera interior: optics side.

etching, oxidation, or metallization are readily visible with a resolution of 1/100 of the wavelength from the illuminating source.

The reference hologram might also be generated by using a computer. This could be called a holographic test plate, and would be used in a manner very similar to that of a test plate in optical fabrication–the computer-generated hologram providing the prescribed contour. A hologram taken of the unit in production would then be superimposed over the reference and viewed as a real-time hologram. An interference pattern of straight lines would indicate a perfect match (ch. 6). The computer-generated hologram can be of special importance in prototype stages where no previous holograms exist to verify the required contouring (ref. 97).

Magnifying Holocamera

Under contract to NASA, D. Close of the Hughes Research Laboratory has developed a prototype holocamera for possible use in the Apollo program. The function of this camera is to take microscopic holograms of lunar surface material while the astronauts are on the moon. A holographic approach was chosen because of the requirement for a large depth-of-field at high resolution. The returned holograms will allow scientists to scan the entire object

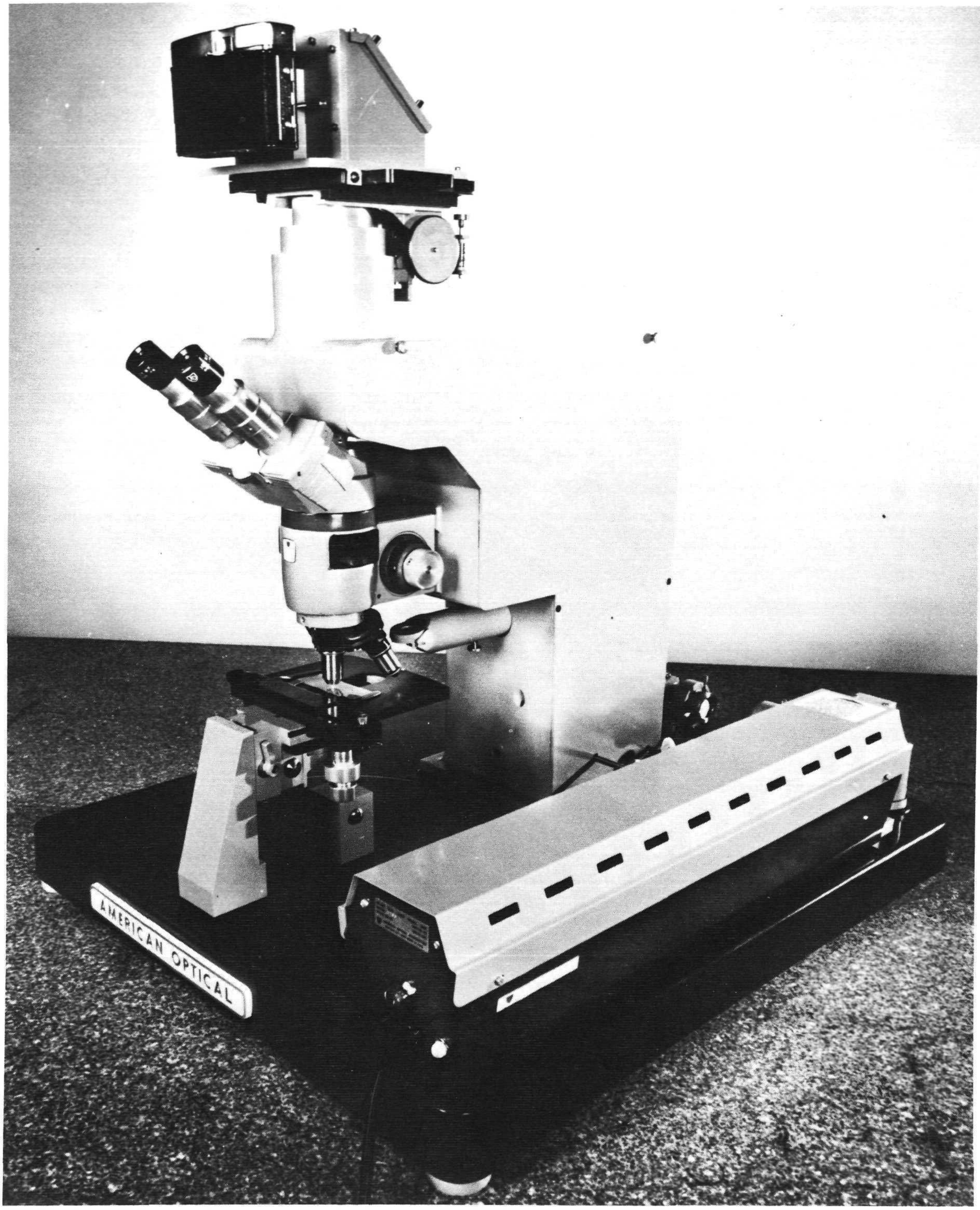


FIGURE 25.–Commercial holographic microscope.

volume using a conventional microscope, a procedure which is not possible with ordinary microscopic photography.

Holograms made of "artificial moondust" have already shown good results (fig. 23). Magnification as high as 52 X has been used on the individual holograms with acceptable results. Speckle was apparent but not very distracting; the superposition technique was employed to reduce it.

Because this camera was developed for use on the lunar surface, it can function in an extreme thermal and vacuum environment and can withstand launch vibrations. These characteristics lend it ideal potential for many other uses, including a portable holographic camera for earth applications such as nondestructive testing and remote interferometric measurements (ref. 98). Figure 24 shows the interior of this prototype camera.

COMMERCIAL DEVELOPMENTS

Complementing the knowledge gained during a contract with ERC, American Optical has developed a commercial holographic microscope (fig. 25) that allows comparison of successive dynamic events through either double-exposure time-differential holographic interferometry or real-time holographic interferometry (ref. 99). Its basic principles of operation are diagrammed in figure 22b. This instrument makes possible the observation and recording of all sorts of microscopic phenomena such as crystal growth, bacteria movement, and tissue growth; surface changes under such influences as heat, stress, fatigue, and flame; phase changes in transparent materials like nerve cells and plastic fibers; the reaction of liquid crystals, particles, and aerosols to outside influences; and remote data gathering.

R. F. van Ligten has used this type of instrument to investigate fresh human blood cells for ERC, and the Naval Medical Research Institute has used the same technique to investigate the effect of pressurization on blood flow in the capillaries of a golden hamster's cheek pouch. An investigation of the use of a remote automatic holographic microscope to study life with landing probes also has begun.

THE FUTURE

A technique called the "uncorrected optics approach," attributed to L. Toth and S. A. Collins, may find wide future application. It involves the insertion of a high *f/n* lens between the object and the hologram while recording, and subsequent use of the same lens in the same position during reconstruction. This approach achieves greater depth of focus and a larger field of view; it eliminates during reconstruction the aberrations introduced while recording; and it relaxes the resolution requirements on the hologram material, since the magnified image is recorded on the hologram. These characteristics may allow the use of less conventional holographic materials in the future.

Repositioning the lens is obviously critical because the aberrations are accentuated by poor positioning. Some image quality is also sacrificed with the large-diameter uncorrected lens. The uncorrected optics approach has already been used to study crystal growth from the melt. Both the corrected and uncorrected optics methods (with a lens between the object and the hologram) allow standard microscopic techniques during reconstruction. Thus, dark-field illumination and phase-contrast microscopy are possible without altering the hologram. For this reason, these two methods show the most promise for potential use (refs. 93, 100 and 101).

One variation of holographic microscopy is the projection of highly reduced images onto integrated circuit materials that are to be etched. The direct projection of the image into the photoresist layer using a lensless hologram seems a promising way to eliminate the intermediate photographic mask now used during integrated circuit production. These masks are unreliable and have short lifetimes. The alternative of using conventional image projection requires highly corrected and costly optical components and systems (ref. 102).

CHAPTER 6

Holographic Interferometry

An exciting and major practical application of wavefront reconstruction was discovered early in the development of holography. Several independent groups of workers discovered more or less simultaneously that two or more three-dimensional holographic images could be compared by a simple superimposition. The most significant aspect of this phenomenon is that the nature of the two or more comparable holographic images can be greatly varied. Both can be stored and recorded on the same film, or recorded on separate films and then superimposed on each other. A stored image and a real object can be superimposed for comparison in real time. The object beams used to form the holograms can be transmitted through the subject or reflected from a moving subject. Furthermore, the time interval between generation of the separate holograms can be varied from a few tens of nanoseconds to days or even years.

If the two or more holographic images are not identical, then "interaction fringes" are formed from the composite superimpositions. These three-dimensional fringe structures describe any differences between the exposures caused by movement of the object or by a change in the amplitude or phase of the object or reference beam. Thus a change in the density or index of refraction of the media through which the light beams are propagated, or a shift of the reference beam source location or light frequency, can be readily detected. All of these principles are used in forming various types of interference holograms and are the basis for the holographic applications described here. These types of interferometric images can be obtained with continuous wave lasers of modest power or with extremely high power Q or mode-locked switched pulse lasers.

This great flexibility in laser requirements and in setup complexity makes possible the application of holographic interferometry techniques to a very wide spectrum of scientific and commercial needs.

NASA RESEARCH AND DEVELOPMENT

NASA activities in interferometric holography may be summarized by the following list:

- Evaluation of arc lamps
- Contour measurement
- Mechanical vibration and shock analysis
- Continuous wave vibration mapping
- Flow visualization
- Nondestructive testing
- Film and surface contamination measurement
- Construction defect determination
- Material evaluation
- Quantitative interferometry
- Subfringe measurement and detection
- Wind tunnel, shock tube and ballistic range measurement and monitoring

Two applications developed by NASA have already shown commercial worth. Holographic methods have been used to accurately measure the surface contours of microwave antennas up to 9 ft in diameter, at time and cost savings compared to previous methods. Holographic evaluation of high intensity lamps has led to the successful design of higher intensity arc lamps, and the same technique can probably be applied to production lamp testing or as an aid in the design of longer burning lamps.

Evaluation of Arc Lamps

One of the most successful NASA applications for interferometric holography was in understanding compact arc lamps, leading to the design of brighter, more efficient xenon compact arc lamps. At 800 nm, the luminance of these lamps was increased about 30 percent by correspondingly decreasing the area of the arc spot. This modification in design was possible after detailed study of the efficiency of heat dissipated from the anode tip due to the convection flow

of gas over the anode. A holographic interferogram of the area around the anode tip disclosed the fringe shifts in the gas layers adjacent to the anode surface, and these clues to the nature of the gas flow provided the means of improving the design to increase the output of light.

A hologram of this type (fig. 26) is formed by a double exposure from a pulsed laser. The first exposure is made with the lamp in place but not operating; the second exposure is made a few seconds later after the lamp has achieved an equilibrium state at a full operating condition. The difference fringes

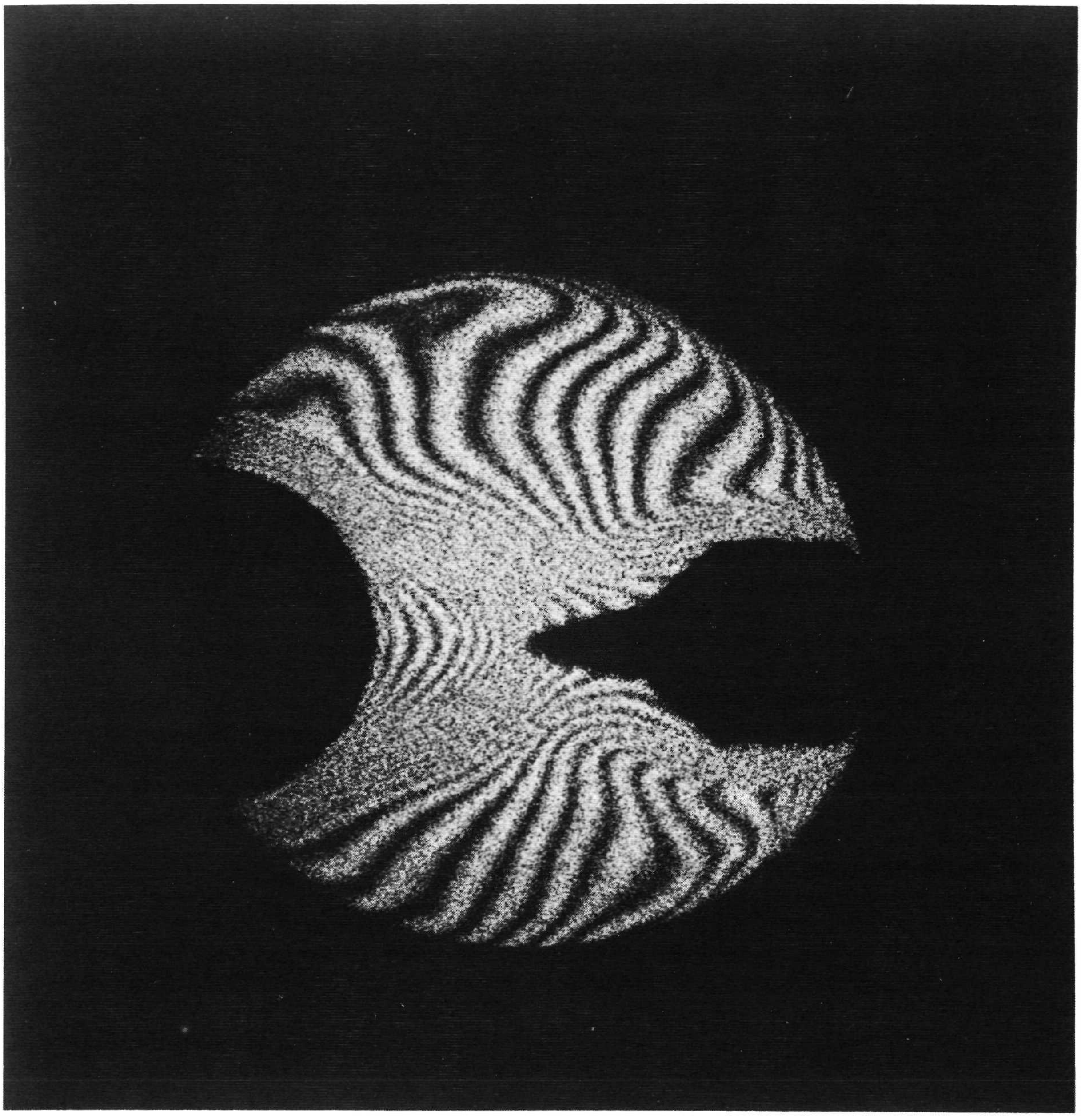


FIGURE 26.–Holographic interferogram of operating arc lamp.

are thus due to a change in medium within the lamp through which the object beam passes. Amplitude and phase shifts in this medium are caused by the varying temperatures and densities of the gas layers in the proximity of the anode (ref. 103).

Potential applications appear to exist, based on these developments, for investigating a variety of fluid flow and heat transfer phenomena. Likely candidates are such processes as nucleate boiling of cooling fluid within the anode, flow in the expansion throat of a CO_2 gas dynamic laser, modes of cryopumping action, convection of gas paths and surface turbulence in a flowing gas, and deformation and creep of surfaces caused by gas absorption.

Contour Measurement

Holography has recently been applied by the TRW Systems Group to accurate measurement (0.001 in.) of the shape changes of large parabolic antennas (9 ft diameter) under space-simulated conditions. The antennas are placed within a continuously pumped vacuum chamber, with front and side solar simulators to visualize the deformation of the antenna surfaces under full sun, side sun, and simulated deep eclipse. Previously, photogrammetry had been used to make measurements to an accuracy of 0.002 in., but this process involved visual scanning of stereophotographs and delayed plotting of a contour map under computer control (ref. 104).

TRW developed under separate contract a holographic interferometer technique and instrumentation for producing contour maps on a near real-time basis (fig. 27). The technique was first discovered during an investigation of holographic instrumentation for ARC. It was observed that if an object was illuminated by a pulsed laser emitting two displace frequencies simultaneously, range contours were generated on the hologram of the object. Previously, range contours had been observed only when objects were lighted by two separate continuous wave (cw) frequencies from two different lasers. Figure 28a shows the generation of range contours 23 mm apart by two neighboring frequencies, while figure 28b shows 8-mm contours generated by frequencies farther apart (refs. 105 through 108).

This contouring technique was the basis for a NASA Tech Brief describing an optical long-range contour mapping concept for which NASA has a patent application. The single pulse aspect of this technique makes possible its application even to moving objects. However, a major limitation of its use at long ranges is the enormous laser power level required (ref. 109).

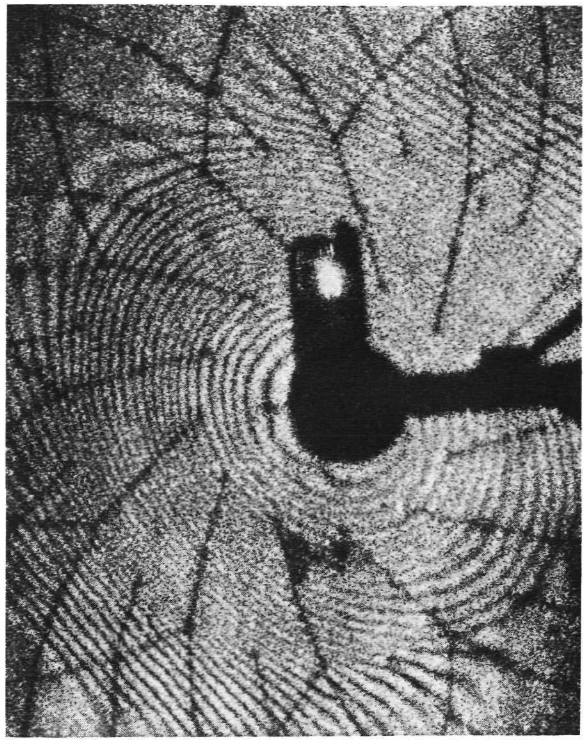


FIGURE 27.–Holographic contour map of a portion of a spacecraft microwave antenna.

Mechanical Vibration and Shock Analysis

Impressive gains in the understanding of mechanical vibrational and shock processes have been made through special holographic analyses. Several NASA centers and at least three contractors have been active in this area of technology. Experiments have been conducted with the loading of thin-walled cylindrical shells; wave propagation in circular cylindrical and conical shells; vibrational modes of heated plates; transverse vibrations of beams and plates; wave propagation in beams; and vibration, flutter, and transient analysis of thin metallic panels.

JPL recently completed a series of definitive experiments establishing a partial explanation for the premature failure of thin shells under a buckling load. Figure 29 shows a series of holographic fringe patterns illustrating the growth of prebuckling imperfections that contribute to the initial failure of the

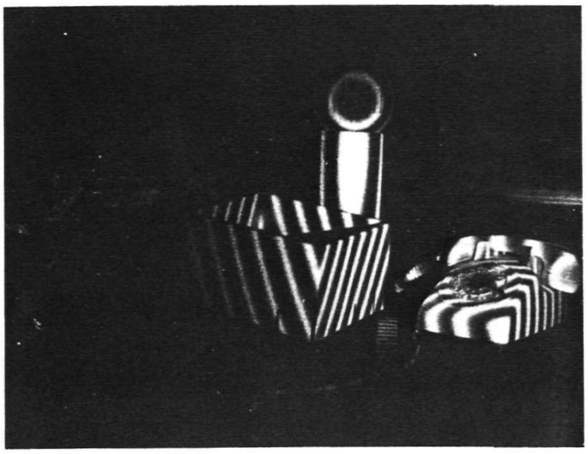


FIGURE 28a.–Initial discovery of holographic contours (with 23-mm interval).

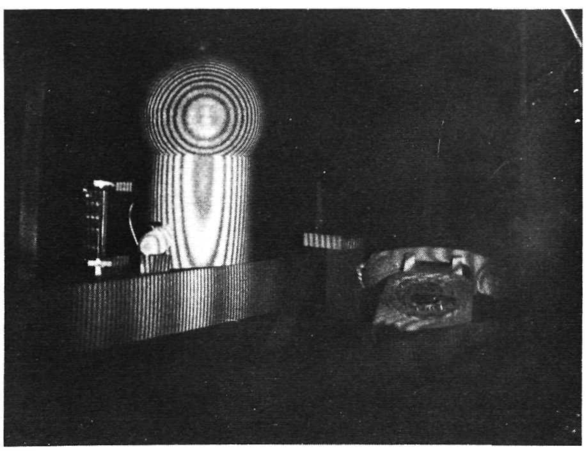


FIGURE 28b.–Holographic contours with 8-mm interval.

shell. Double-exposure holographic interferometry is an ideal technique for this measurement. It is a noncontact technique and also allows mapping the entire surface at once. The equipment setup is a normal type of double-exposure reflection holography, using a small increase in compression load between each exposure (refs. 110 and 111).

Vibrating beams and plates have been studied with strain gages or capacitive displacement sensors for some time. However, these devices cannot simultaneously measure all the points along a vibrating structure, and the devices themselves may disturb the natural vibrational modes of the test piece. Another conventional research method is the formation of Chladni sand patterns at lower frequency vibrational levels, but this requires level positioning of the test piece, and the resulting patterns only indicate the nodal lines, not the shapes. Holographic interferometry can overcome all these limitations.

The experimental arrangement used by TRW to measure transverse vibrational modes of a cantilever beam is shown in figure 30 (refs. 112 and 114). A simpler experimental setup was arranged to take time-averaged reflection holograms of an excited plate. The plate was a simply supported sheet of aluminum 8 in. wide by 10 in. long by 1/16 in. thick. Figure 31 is a hologram of the plate in its normal mode, while figure 32 shows a high frequency modal pattern. At a frequency of 20 892 Hz, the 13th order horizontal and the 11th order vertical harmonics have been excited, and the center point of the plate, attached to the driving transducer, is distorted (note how dark it is). These holograms were taken by a time-averaged exposure, but the experimental conditions were first adjusted to stable resonant frequencies by viewing the plate through a stored beam hologram in real time (refs. 112 through 115).

Recently a NASA contractor began measuring the vibrational modes of plates between 1000 and 2200° F to study the stress and strain expected on the panels of the space shuttle. One of the major problems associated with such measurement is the distortion of the holographic fringes caused by convection currents adjacent to the heated test specimen. This problem has been solved by using double-pulse interferometric holography. The interval between the pulses is shortened to 50 μsec, and the relative phase of these pulses with respect to the vibrational amplitude of the plate can be carefully controlled. In this short time interval, the thermal convection currents introduce negligible fringe shifts, so that the vibration modes of the plate can be observed without interference.

Included in this same work was a study of the details of mechanical wave propagation in circular cylindrical and conical shells with and without flaws and cutouts. The progress of the waves traveling along these structures was determined by a series of double-pulsed holograms and compared with a computer analysis. The results of the reduced holograms were expressed graphically in terms of radial displacement versus axial position along an aluminum shell. Holographic analysis is expected to aid in development of wave propagation theory and to effect improved methods of detecting and measuring the

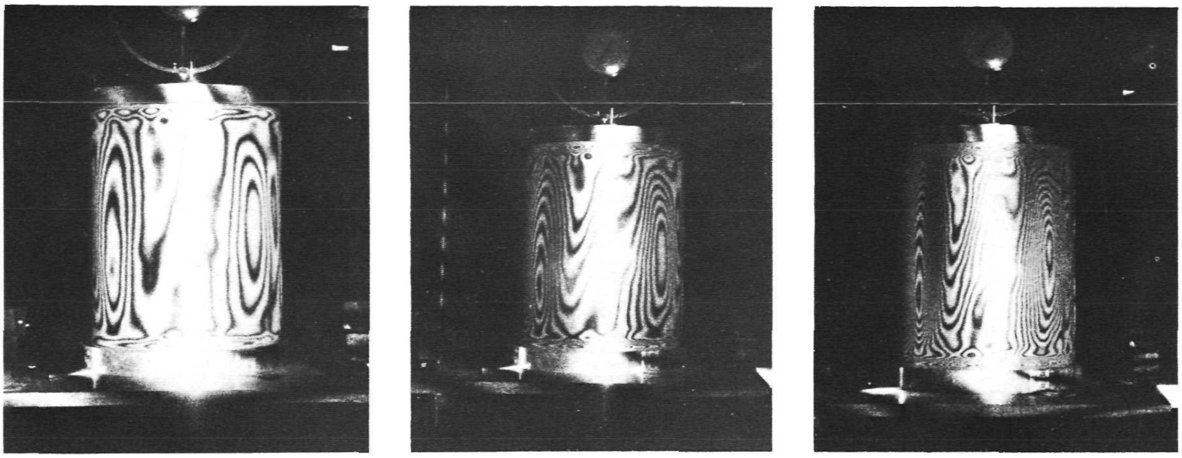


FIGURE 29.—Thin shell interferogram at various prebuckling loads (a–72%, b–77%, c–84%).

effect of structural flaws on the strength and endurance of mechanical members (refs. 116 through 118).

Continuous Wave Vibration Mapping

Great progress has been made by ARC in establishing the time-averaged holographic method in an operational test facility. The cw work previously discussed required that all parts, including the cantilever beam, be mounted on an 8000-lb granite table, shock-isolated from the laboratory surroundings. R. Brown of ARC has devised a fringe stabilization system that seems to bring cw holographic interferometry closer to commercial realization. The purpose of this system is to prevent the motion of fringes during exposure of the hologram, even if some of the optical components or test pieces are not completely isolated and immobile (fig. 33).

Basically the beam combiner located behind the holographic plate is designed to monitor the type of fringe at a given point and determine the movement of a fringe across the hologram. The photodetector and servo-electronics translate the speed and direction of the fringe's movement into a command to change the path length of the reference beam to the hologram and thus stabilize the fringe's position. This is indicated by a constant signal to the photodetector. The extent of the stabilization possible depends on the type of motion to be compensated; linear motion can be compensated equally across the whole hologram, but rotational motion can be stabilized exactly only at a single point.

Plans have been made to use this vibration mapping system to study structural prefailures, correlations of failures with mechanical tests, and optimum shaketable excitation points for complex structures. Certain transient phenomena of a nonrecurrent nature are not suitable for analysis with cw holography, but this vibration mapping system is flexible enough to be used with pulsed lasers for such investigations (refs. 119 and 120).

NASA has also been investigating complex techniques for modulating the phase of the reference beam to vibrating and fluttering thin metallic panels. Two specific techniques have been demonstrated: (1) shifting the phase of the reference beam with respect to the object and (2) using a shuttered laser system to strobe the illumination and reference beams and "freeze" fringe motion. The phase of the observed nodal fringe patterns may be determined; i.e., whether a given bright fringe on the hologram was caused by a node or an antinode vibrational pattern (refs. 121 and 122).

Flow Visualization

Holography has been studied by NASA Centers as a way of making visible elusive changes in fluid flow, fluid temperature, and fluid density associated with aerodynamic phenomena, thermal gradients, liquid flow constructions, rocket nozzles, and expansion chambers. Such work at LRC, ARC, and MSFC has centered on means of monitoring the dynamic events occurring in wind tunnels and rocket test stands.

534–778 O–74—4

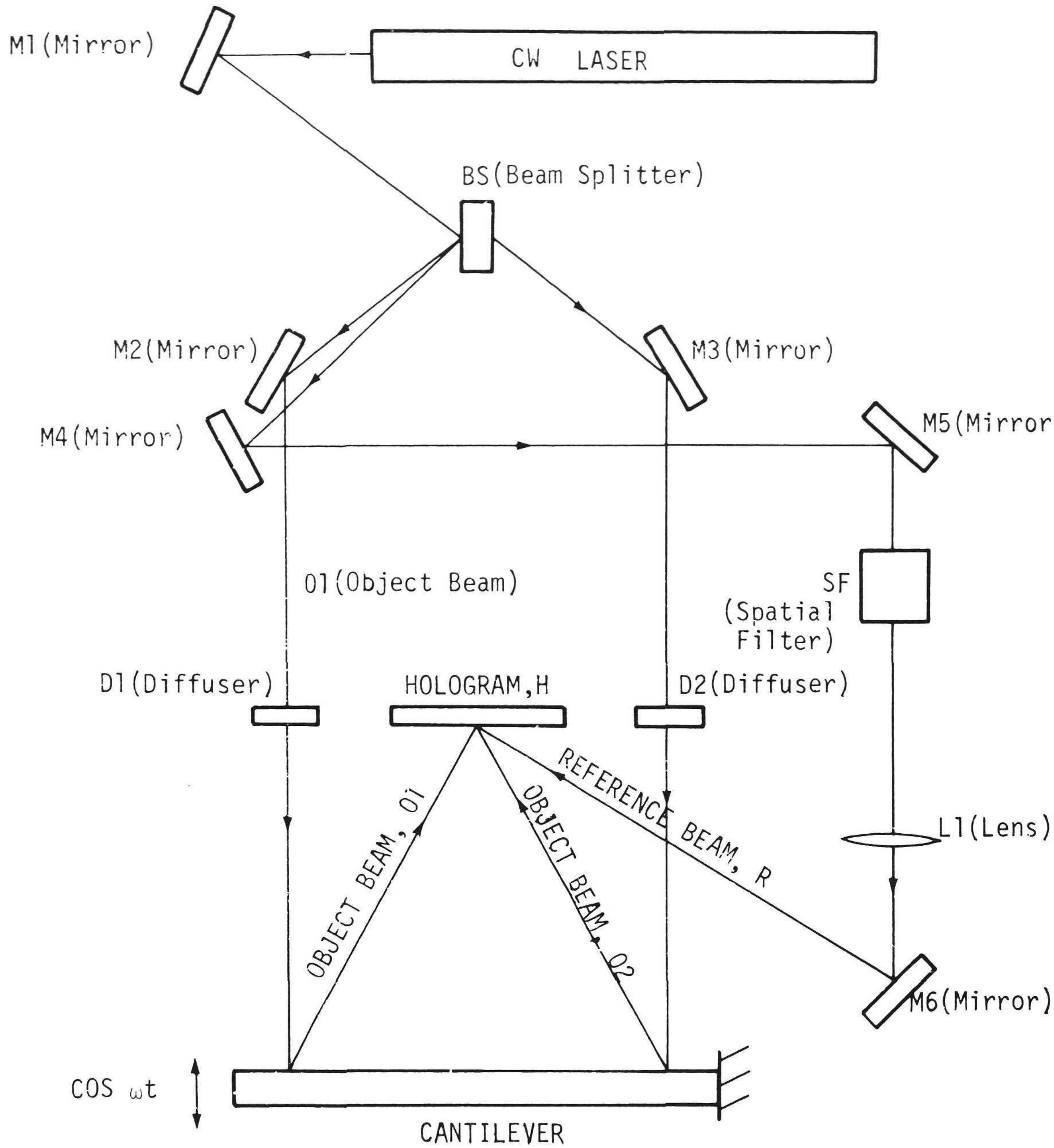


FIGURE 30.–Apparatus used in making holograms in the cantilever beam.

Early development at LRC to replace the conventional shadowgraphs and Schlieren techniques used in wind tunnels led to establishment of flow visualization techniques using holographic moire patterns. These earlier photographic techniques allowed qualitative flow analyses that could not quantitatively measure density, temperature, or pressure. Quantitative devices also had drawbacks: The use of probes changed the original flow pattern, and conventional interferometers required costly, high-quality transmission optics and highly precise mechanical adjustments that could be affected by wind tunnel vibrations.

The LRC workers found that using superimposed

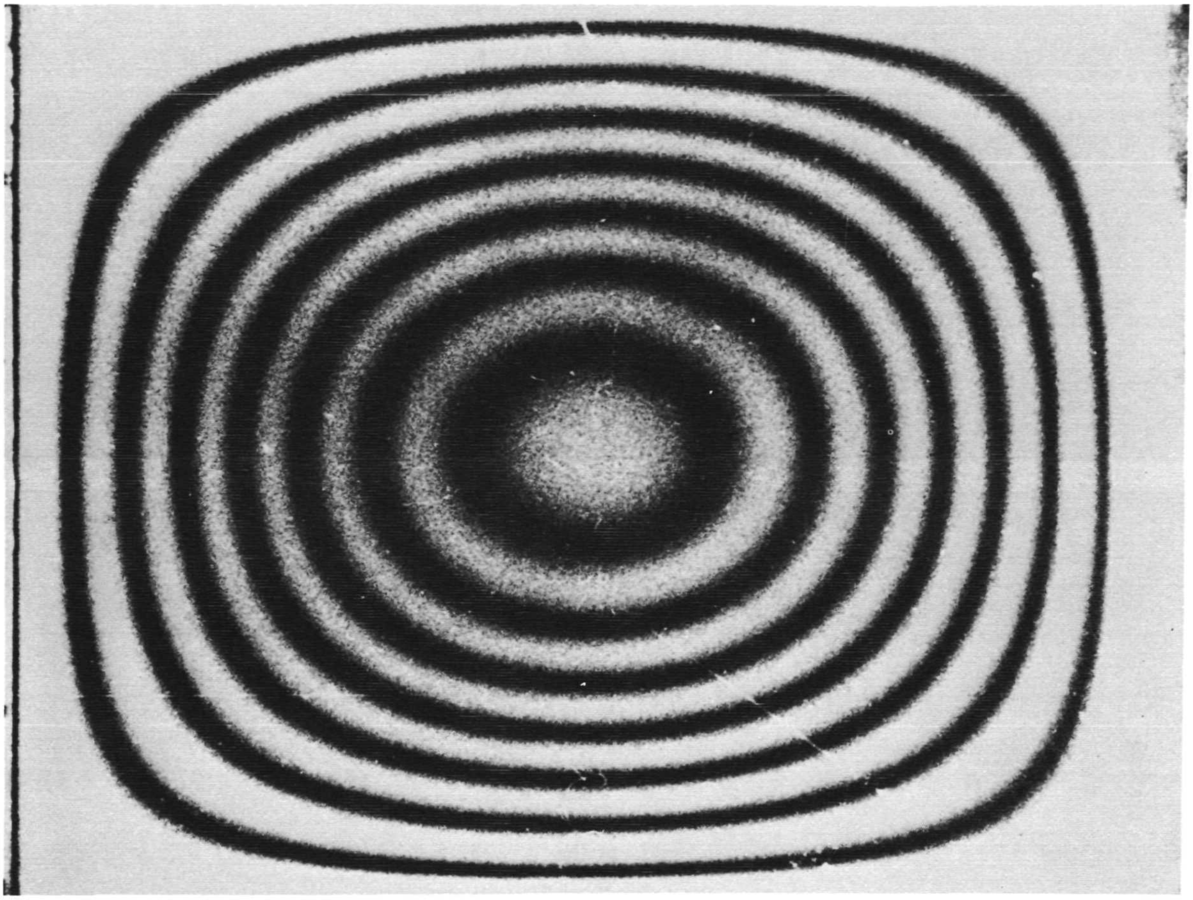


FIGURE 31.–Hologram of fundamental mode of plate–162 Hz.

moire fringe patterns produced holographically from a cw laser would solve all these problems except for vibration, and that even the sensitivity to vibrations could be reduced. The fringe pattern could be monitored in real time and did not require as precise a repositioning of the original hologram as is required with other holographic methods. Changes in the test section produce a magnified perturbation of the normal moire fringe pattern, and the sensitivity of the system can be increased by increasing the spacing between the fringes (in the limit, this is called the infinite fringe width condition). Figure 34 shows these principles applied to a candle and its heated air stream.

ARC and the TRW Systems Group have also experimented with finite fringe holograms, and NASA Tech Briefs have been published on the subject (refs. 123 through 125). Investigations at ARC have culminated in development of a full-scale operational test facility to monitor, measure, and visualize flow fields in a wind tunnel (ref. 126).

Nondestructive Testing

Nondestructive testing of all types of mechanical and aerospace structures is of great practical interest. Although most of the holographic techniques developed for this purpose have not conclusively established their worth, they have given very favorable indications of successful performance during feasibility tests.

- Research at MSFC is in progress, ranging from the testing of titanium welds to arrangements for monitoring contaminated optical test blanks in space.

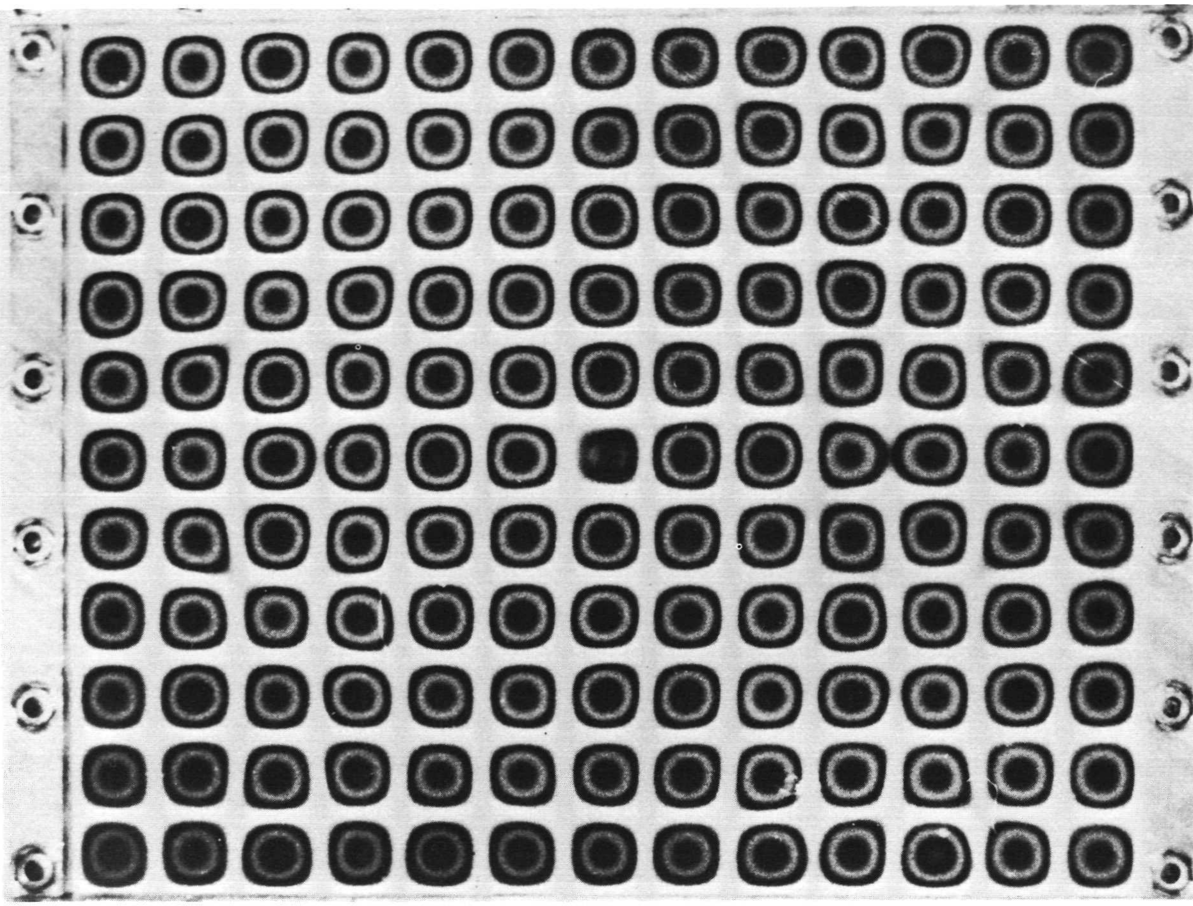


FIGURE 32.–High-frequency model hologram.

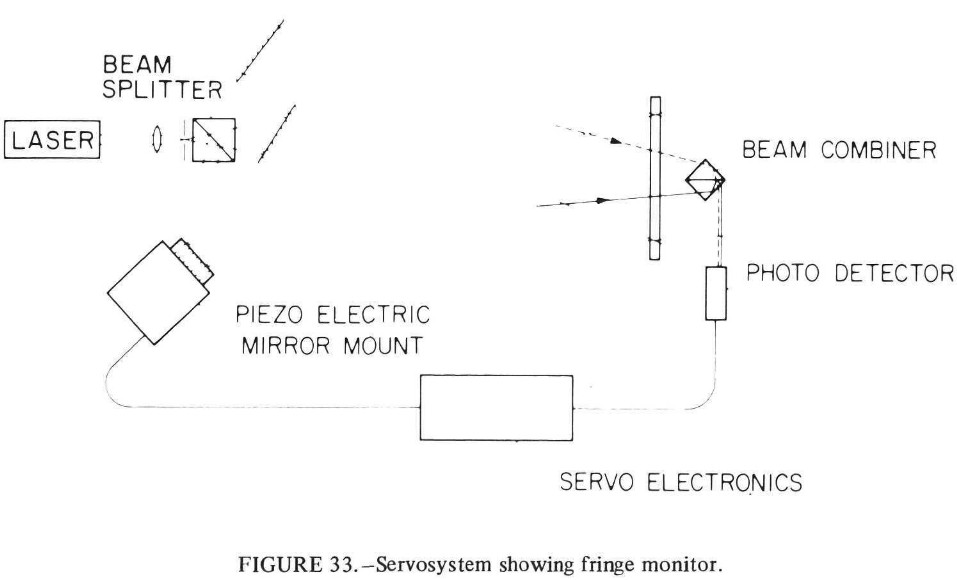
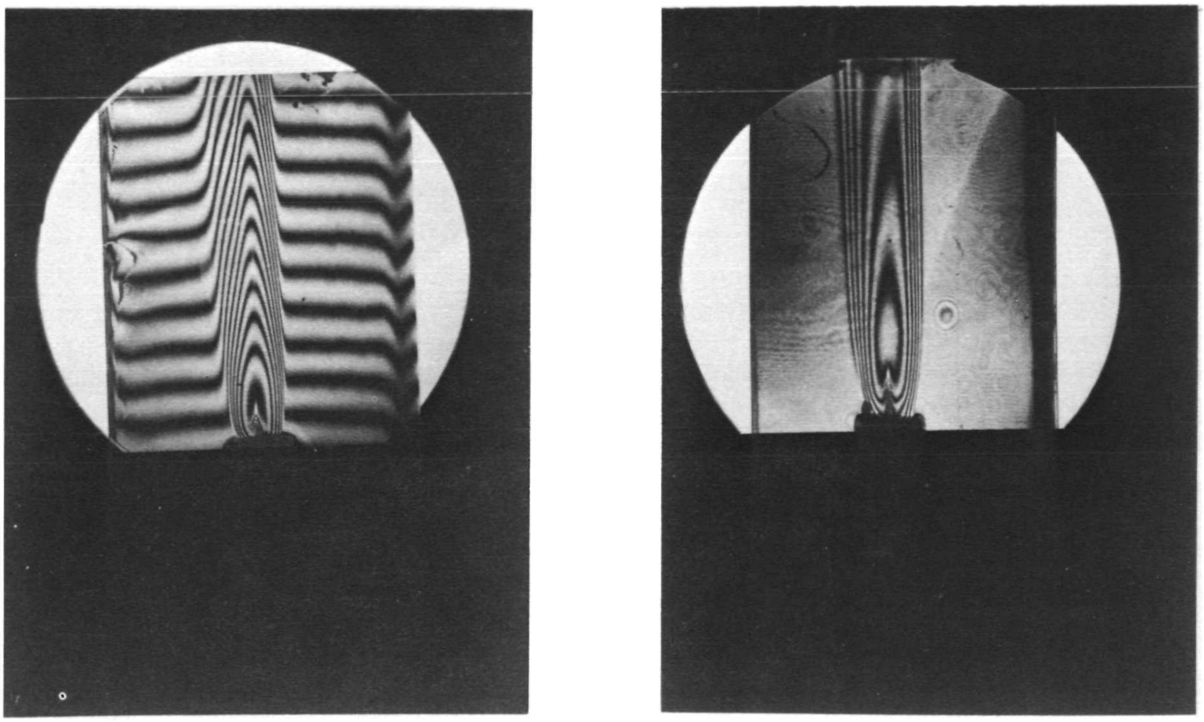


FIGURE 33.–Servosystem showing fringe monitor.

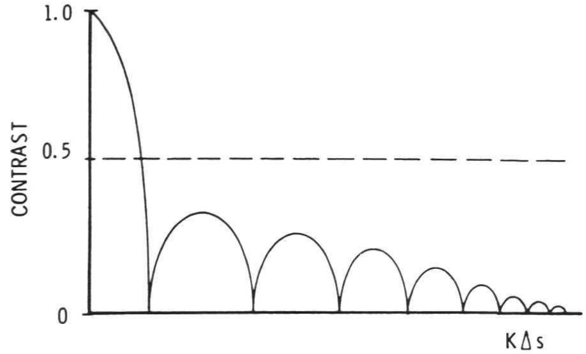


finite fringes infinite fringe

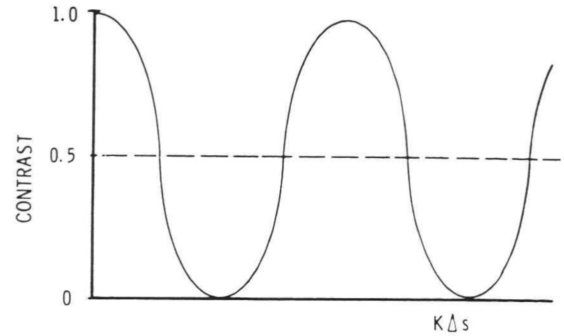
FIGURE 34.—Real-time flow visualization using holographic moire patterns.

- GSFC and MSFC are planning holographic interferometric test facilities to measure simulated space flight effects on various spacecraft systems and components and to develop methods for quantitative nondestructive testing of spacecraft structures.
- LRC and its contractors are developing techniques to test bonded and honeycomb materials and to detect microcracks in structures.
- JPL has shown the feasibility of testing solid propellants for defects, indicating a strong potential for application to a number of different materials.
- ARC and its contractors, TRW and the University of Arkansas, have developed techniques to monitor subfringe changes of holographic interference patterns.
- The University of Michigan, although under contract to NASA for a number of years, has independently discovered and developed several advances in applying holography to additional fields and situations (see next section).

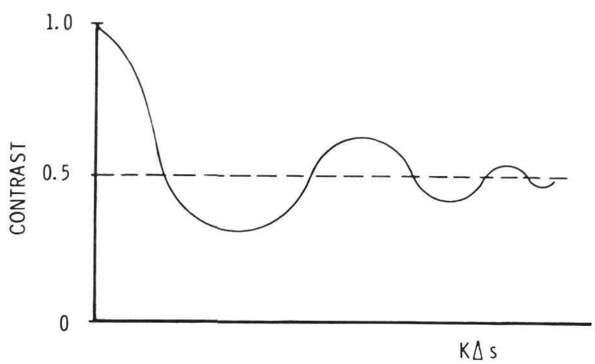
Some of the most extensive work in holographic nondestructive testing has been carried out in J. William's group at MSFC. He recently pointed out that although the three major types of interferometry (time-averaging, double-exposure, and real-time) produce about the same quality of interaction fringe patterns, the quantitative contrast of these fringe patterns as a function of their order which is proportional to displacement distance differs markedly. This difference is seemingly a detail of the process, but it can have a significant impact on practical results. The three principle cases (fig. 35) clearly show that if the added complications and complexities can be tolerated, double-exposure interferometry should give higher contrast, especially if displacements exceed a few wavelength orders. It also shows the importance of adjusting the pattern by fringe control so that the nodal fringe, zero order, occurs near the fault or defect (ref. 127).



a. Time averaging holograph



b. Double exposure holograph



c. Real-time holography

FIGURE 35.–Contrast comparison of three types of holographic interferometry.

Film and Surface Contamination Measurement

Space probes, vehicles, and stations orbiting near earth or passing through the tenuous upper atmosphere of earth or other planets are expected to be bombarded by particle clouds and contaminated by the absorption or adsorption of thin films of foreign material. The effects of these foreign deposits on the lifetime and performance of space systems is of considerable interest to NASA. For example, such deposits on the entrance aperture of earth resources-surveillance-sensor systems could seriously attenuate and distort the incident energy.

Instrumentation has been developed at MSFC to record this buildup of contaminates on a transparent or reflecting substrate in a simulated space environment. The substrate is contained in a vacuum chamber. Figure 36 is a double-exposure interferogram taken on an earlier system showing fringes produced by a thick contaminating oil film. The film was smeared on the optical flat between the first and second exposure. Quartz crystal microbalances will be placed in the vacuum system to collect deposited mass data to be correlated with recordings or motion pictures of the interferograms; deposit of films or particles will be recorded or viewed in real time.

The new system concept (fig. 37) can record either a reflectance or a double pass transmittance hologram, or both simultaneously, depending on whether the substrate is semitransmitting. Such a dual system to record the weight and the thickness of foreign particulate or film buildup will have wide application. The major limitation at present is the thickness of the film that can be detected. The systems just described can measure thickness down to 0.32 μm. The use of ultraviolet interferograms increases the sensitivity to 0.17 μm. In addition, NASA has been doing considerable work on subfringe holographic interferometry, and these techniques are potentially capable of determining thicknesses of 1.7 to 3 nm.

These techniques may also solve nonaerospace problems involving measurement of thickness or

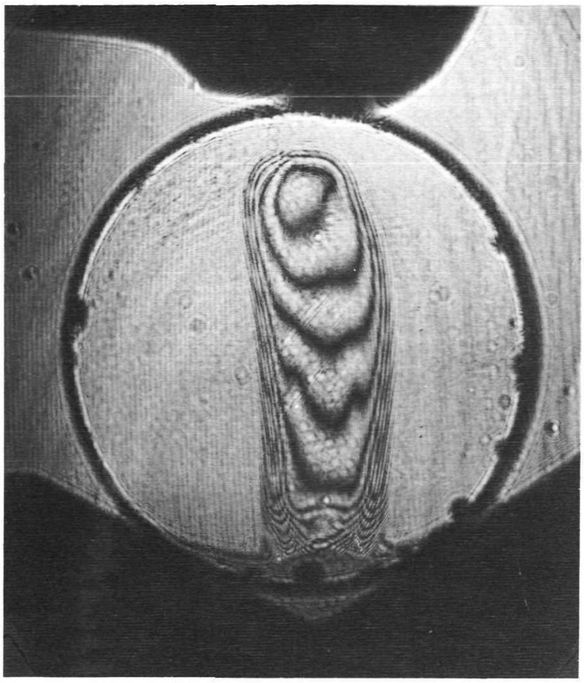


FIGURE 36.–Double-exposure holographic image of contaminated optical flat.

uniformity of a substance over an area. For example, a bottle manufacturer might need to determine the uniformity of a plastic coating applied to his bottles during fabrication (refs. 127 through 130).

Construction Defect Determination

The holographic detection of construction defects or material faults has been intensively investigated by NASA. MSFC was able to detect faults in a metal-to-metal weld between two pieces of titanium declared perfect by x-ray analysis. When an entire printed circuit board was recorded as a holographic interferogram, areas of suspect construction and questionable solder joints could be determined from the image (refs. 128 and 129).

Major work on developing techniques for the analysis of faulty material or structures has been carried on by United Aircraft Research Laboratory (UARL) and LRC. UARL has completed an extensive study on composite samples, consisting of various multiple-ply, layered arrangements of boron- and carbon-epoxy, previously bonded and then sandwiched between aluminum and titanium substrates with adhesives. Each sample was fabricated with deliberate flaws between the sandwich substrates: For example, steel bags and teflon spacers were inserted in place of the prepregnated layers. Attempts to fabricate flaws caused by weak adhesives between the layers and the substrates were not successful.

The prepared samples were examined by holographic cw interferometric techniques and by infrared scanning. Real-time viewing was used to determine thermal stress reactions, while time-average holography was used to record interferograms of the acoustically excited samples. The time-average interferograms proved better than infrared pictures for detecting these flaws, and much better than thermal stressing. Reliability of detection was not uniformly high for all samples, however, and different modes had to be excited to reveal all observed flaws.

Several obstacles must be overcome with this technique. A method must be found to introduce greater amounts of acoustic energy into the test specimen, and relationships between detected flaw size or shape and overall structural strength must be found if the results are to be properly interpreted. LRC is pursuing the problem of determining the strength of a weak bond as contrasted with detection and location of a total disbond (ref. 132).

This interferometric technique has also proved more reliable than other methods in detecting disbonds in composites made of honeycomb paper cores and aluminum sandwiches. Such composites are being used by the Army for constructing portable hardwall buildings (ref. 135).

Material Evaluation

An intriguing use for holography is the detection of small microcracks and flaws in various types of material. Work is under way at LRC to apply such techniques to aerospace structure testing and monitoring. The University of Michigan has studied the detection of radial microcracks extending from bolt holes in high strength aircraft steel, and has also done extensive studies of stress corrosion cracks (see next section). Although microcracks can be detected by conventional inspection techniques such as dye penetrants, Magnaflux, and visual examination, these methods normally require careful cleaning of the surface plus microscopic examination. Holography is better suited to periodic structural tests on aircraft, rockets, tunnel walls, and building structures.

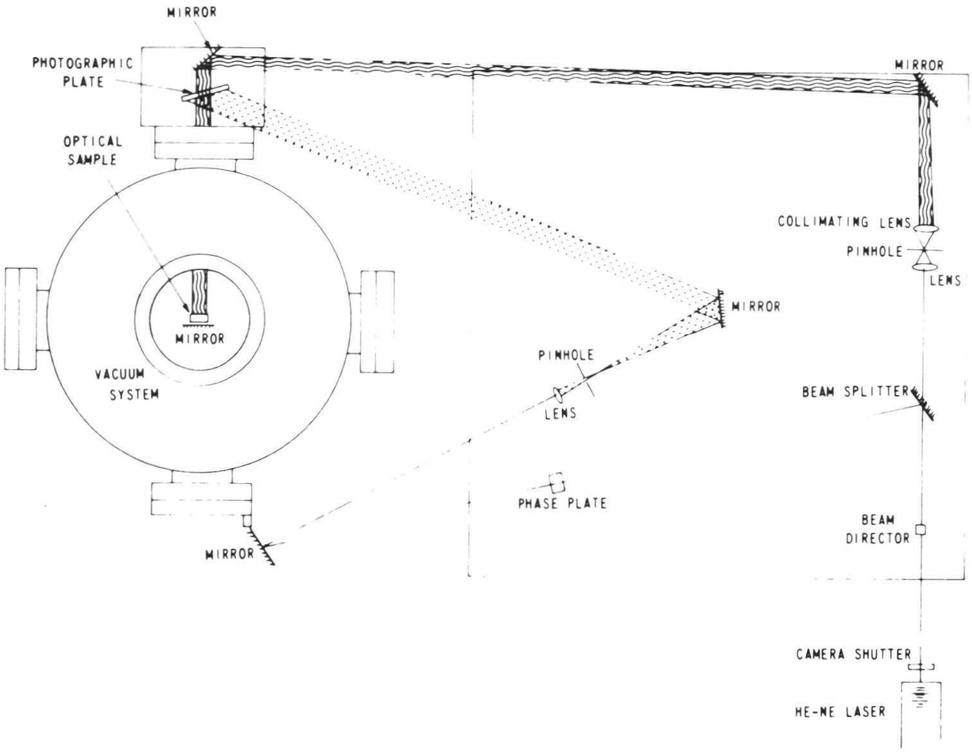


FIGURE 37.–Optical layout of holographic thin film analyzer.

Quantitative Interferometry

Although fringes can be interpreted to indicate a total system shift of one or one-half wavelengths, this total system change cannot always be translated easily back to a corresponding change in the object or specimen under test. For example whether an object is translated or rotated between or during exposures will greatly affect the characteristics of the interferogram. The direction from which the object beam falls on the subject and the reference beam falls on the hologram affects the fringe pattern. Strictly speaking, the exact direction of motion, even if it is a straight translation, cannot be determined without using three interferograms, one for each component of motion. The situation becomes far more complex when a partially transparent subject is considered; then the three-dimensional fringe volume extends both within and out beyond the subject.

At MSFC, some analysis has been done on fringes produced by a general rotation and translation of a minor object between exposures. In a similar series of experiments at GSFC, experimental measurements, determined holographically, were compared to the angular rotations measured by an autocollimator and an inclinometer (refs. 135 through 137). Further projects on quantitative interpretation of holographic interferograms are planned by Manned Spacecraft Center (MSC) and the University of Michigan, especially the measurement and evaluation of object deformations under mechanical stress (ref. 138).

Subfringe Measurement and Detection

One of the greatest limitations in holographic interferometry is the difficulty of varying its sensitivity. For example it might sometimes be desirable to make a fringe shift represent different values of displacement or movement, to read out intervals much less than a fringe, or to count fringe differences accurately in the presence of many closely spaced fringes.

One approach to this problem involves varying the wavelength of the laser light, which slightly alters the magnitude of the change of surface displacement causing a fringe shift. A second approach is recording a single exposure hologram with two simultaneous

frequencies, which greatly desensitizes the fringe contours (ch. 3). A third approach is fringe control.

Fringe control can be thought of as a method of shifting certain higher order fringes on the interferogram to zero or low order fringes. It can lessen the problem but not eliminate it. ARC is expecting further progress from its work in developing subfringe measurement techniques. Another significant contribution is expected to result from the application of the principle of generalized reference beam modulation, discovered and developed from C. Aleksoff's research.

ARC, in close cooperation with the TRW Systems Group, has pioneered in subfringe interferometry. Their efforts began after the discovery that interferometric holograms made of high velocity, low pressure air flows exhibited very few fringes. The series of early TRW double-exposure holograms shown in figure 38 were taken in a ballistic range at progressively lower atmospheric pressures, down to a minimum of 6 mm of mercury. Although a few fringes remain at 60 mm, only about 1 to 1/2 at the most remain at the lowest pressure. These interferograms were made by taking the first pulse exposure before arrival of the bullet and the second exposure 100 μsec later with the bullet in view.

The earliest attempts at subfringe measurement were based on shifting the phase of the subject beam 180 degrees between exposures of a regular double-exposed holographic interferogram. Exact 180-degree phase shift and precisely equal laser amplitude exposures are difficult to stabilize, however, so the "four beam subfringe interferometer" and other such techniques are useful only for applications requiring qualitative results on the order of tenths of a fringe sensitivity (refs. 139 and 140).

Researchers at the University of Arkansas Institute of Technology, under NASA contract, have developed a very versatile technique called "dual exposure holographic interferometry with separate reference beams" (ref. 141). This technique particularly lends itself to subfringe measurement, but it can also be used to obtain finite and infinite fringe interferograms, shadowgraphs, and Schlieren holograms and photographs. As implied by the name, two reference beams instead of one are used in making a double-exposure interferogram. During the reconstruction, the phases between the two reference beams can be varied to accentuate features of the hologram. This difference can be used to measure the subfringe distance between the corresponding image points of the hologram accurately to phase angles as small as 1.5 degrees or 1/240 of a fringe (refs. 141 and 142).

These techniques have not been successfully applied to examining the high velocity, low pressure flows of wind tunnels, shock tubes, and ballistic chambers, primarily because of the highly unstable turbulent boundary layers that plague these devices and the high levels of vibration and flow transients. They should, however, prove useful in more moderate environments such as the measurement of thin fibers, particulate buildups, or birefringent anisotropic partially transparent objects (refs. 131).

COMMERCIAL ENDEAVORS

Production line testing of large aircraft panels through commercial holography has been going on for over 2 years, with considerable cost savings compared to the former ultrasonic and x-ray testing methods. Another aircraft application using holography has been the testing and data gathering for redesign of turbine blades and other jet engine components before the units are assembled. This process has substantially reduced costly jet engine failures during final test runs.

Although at present these two aircraft applications are the only ones that have demonstrated savings, many of the other applications listed in this section will probably show similar results. One promising area is the holographic testing of commercial tires to select those suitable for recapping. Much research and development remains to be done, however, before holographic interferometry is an established commercial technique that is both technologically and financially feasible.

Nondestructive Testing of Aircraft Panels and Honeycomb Structure

Rohr Corporation (Chula Vista, California) has been using cw interferometric holography for the past 2-1/2 years to test aircraft honeycomb panel structures such as wing or body sections. The commercial equipment used can accommodate panels 20 ft long and 6 ft wide. Tests are routinely made on the first honeycomb qualification panel assembly bonded by each production tool. These panels used to be destructively tested, but the present method of holographic testing in conjunction with ultrasonic

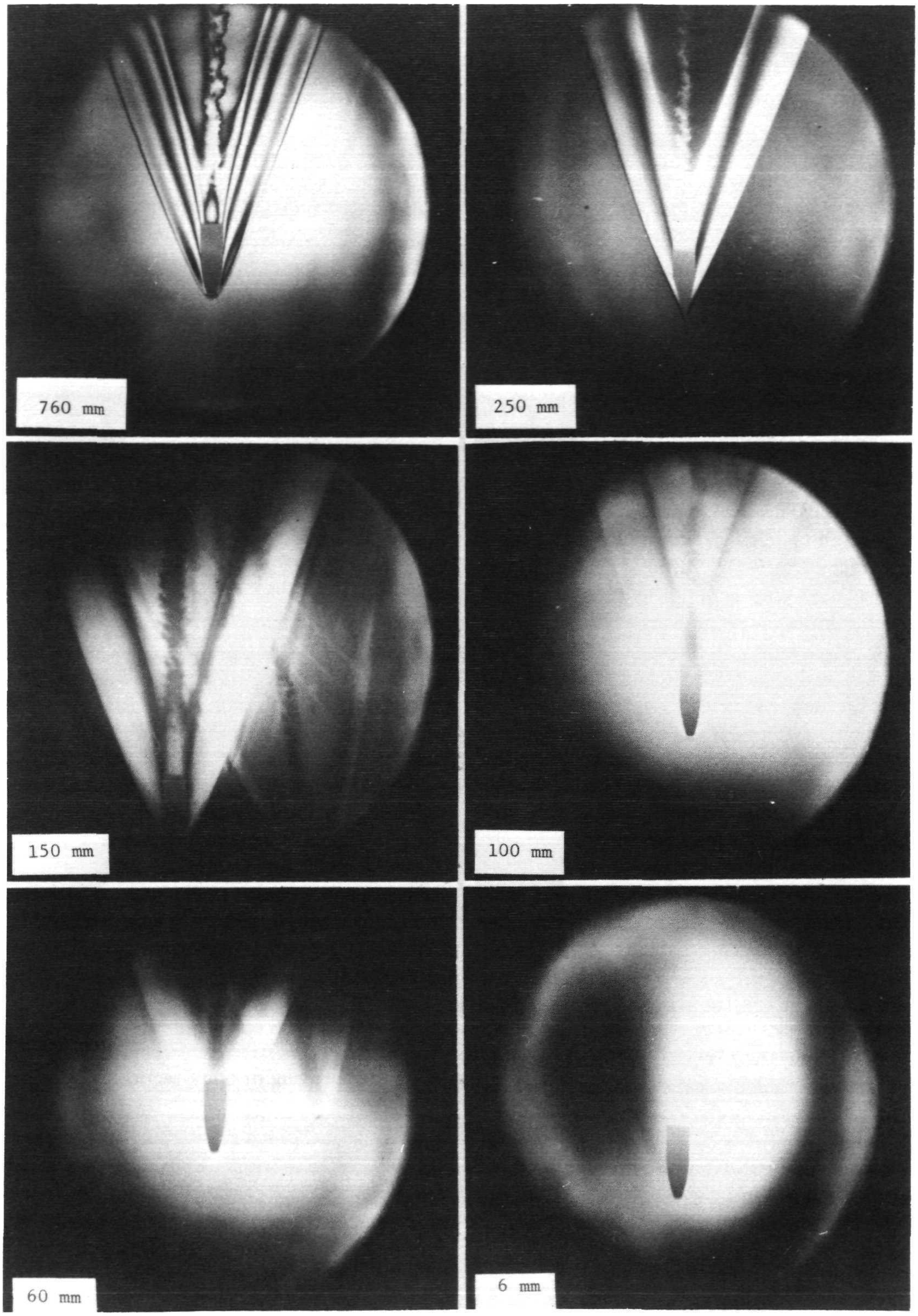


FIGURE 38.–Double-exposure holographic interferogram at various chamber pressures.

and x-ray nondestructive test equipment is cheaper and quicker.

Rohr has used two types of commercial equipment: The first unit (fig. 39) has an argon laser as a coherent light source, while the second, smaller unit uses a helium-neon laser (fig. 40). The panel to be inspected is held in place with a series of vacuum cups. After in-place development of the unstressed panel's hologram, the area to be inspected is heated a few degrees above ambient. Irradiation of both the panel and the static hologram by the laser source then allows the operator to view interferometric fringes in real time. Proper interpretation of the fringe field identifies debonding of the skin to the core and areas of crushed core.

The small unit can inspect about 2.2 sq m of panel per hour, while the larger unit can handle up to 5.6 sq m per hour. These test rates are from four to five times faster than ultrasonics, and more than make up the initial double investment cost of the holographic system over the ultrasonics unit. The manufacturer has concluded that the cost ratio for nondestructive testing using x-rays is 1.5 to 1, ultrasonic testing is 8 to 1, and holography is 1 to 1. These ratios are based on maximum production test rates, 80 percent machine utilization, machine lease, materials, and labor costs (ref. 143).

The typical appearance of debonds on these panels is shown in figure 41. The Rohr Corporation has stated that the holographic test system does not experience a false alarm problem as such, but "you do have to know your structure." The positions of irregularities such as edge members, steps, and transition points must be known, because each of these characteristics has its own signature that could be confused with a true defect. There are over 100 different configurations of test pieces and the test engineer must be familiar with the holographic peculiarities of each piece (ref. 144).

Nondestructive Test Equipment for Tires and Brakes

A commercial tire tester that uses holographic techniques is being studied in the research and

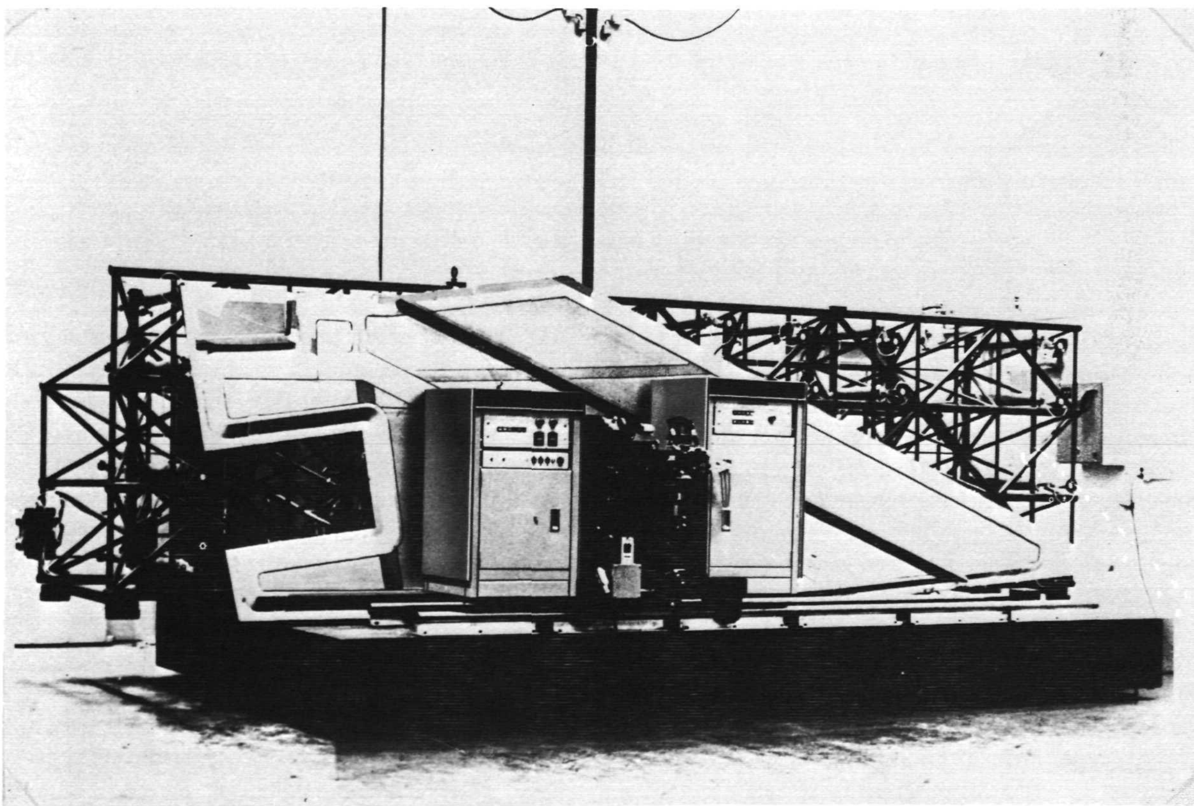


FIGURE 39.—Large holographic system.

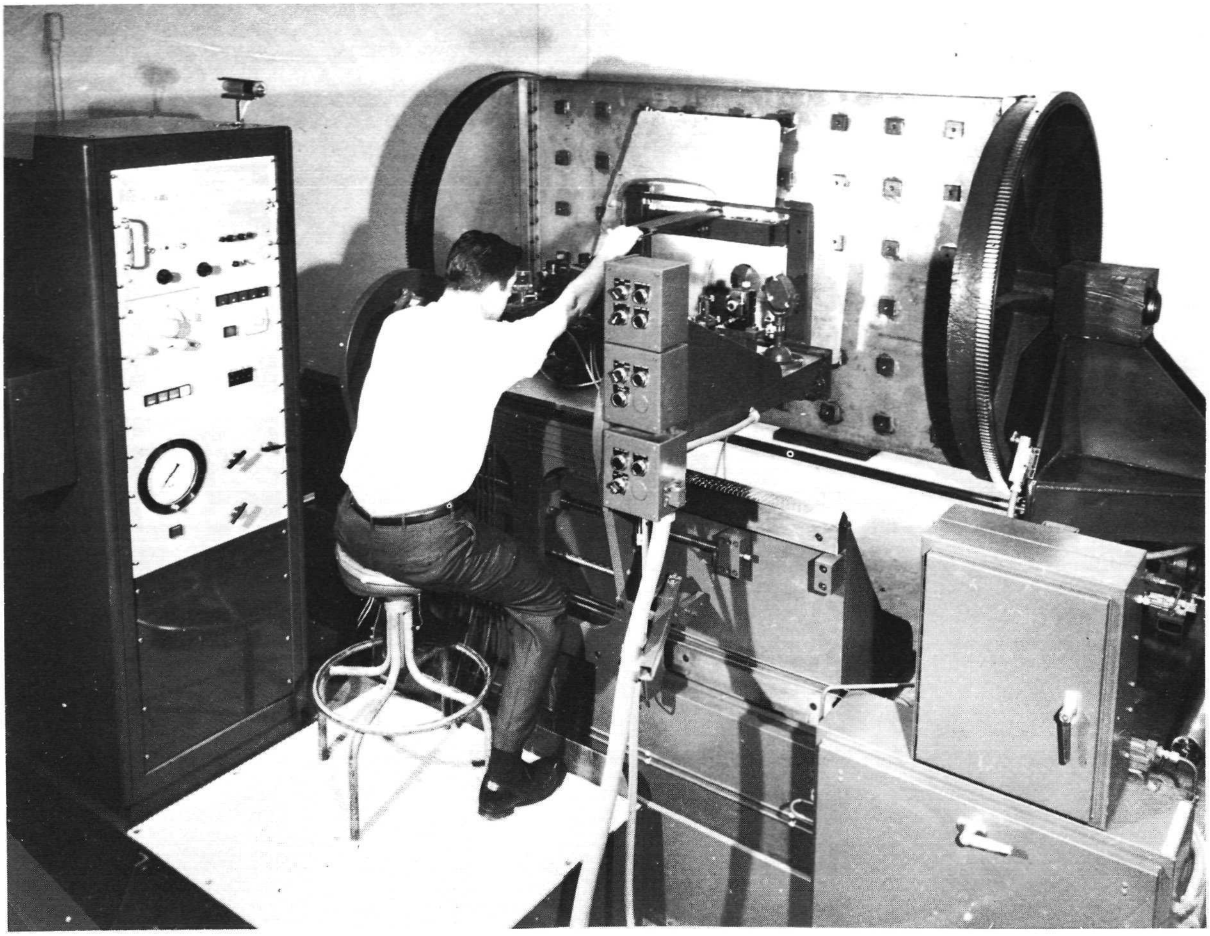


FIGURE 40.–Small holographic system.

development departments of major tire and auto manufacturers such as Royal, Firestone, Goodyear, and General Motors (fig. 42). The device makes a doubly exposed cw hologram of the tire's inner surface; one exposure is made while the tire is subjected to a partial vacuum under the bell hood, the other at normal atmospheric pressure. The photograph in figure 43 shows a reconstructed hologram of a tire with a suspect region (indicated by fringe anomalies) where there may be separations between tread and sidewall; this tire later failed a wheel test. The holographic test can simplify selection of tires for retread (ref. 145 and 146).

The Department of Transportation (DOT) is in the midst of an extensive program to correlate potential tire faults revealed by holographic, x-ray, ultrasonic, and infrared tests with actual wheel and road tests. DOT will be establishing both minimum standards and means of evaluating tires against these standards. At present, Dr. Knabe of DOT believes that for every real fault revealed by holographic testing there are many irregularities that may prove to be false alarms. This analyzer may soon be examining automobile, truck, and aircraft tires for carcass ply separations, belt edge separations, tread and sidewall separations, multiple cord fracture, porosity and voids, and carcass and belt damage (refs. 142 and 143).

Jet Engine and Turbine Testing

Pratt & Whitney Aircraft currently redesigns jet engine parts and components on the basis of holographic analysis. These cw holograms exposed in a time-averaged mode have revealed serious anomalies

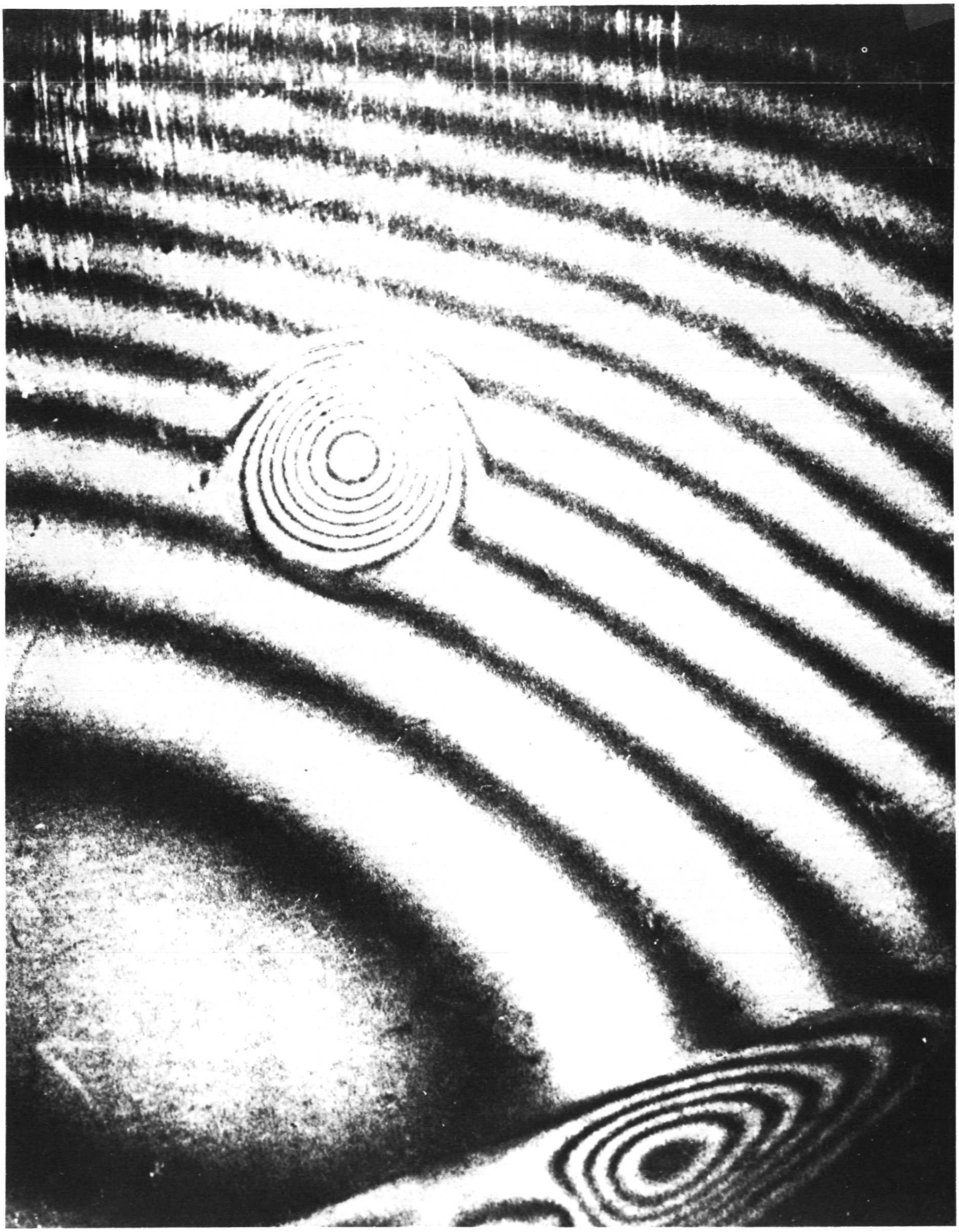


FIGURE 41.–Debonds on adhesive-bonded honeycomb aircraft panels.

FIGURE 42.–Commercial holographic tire tester.

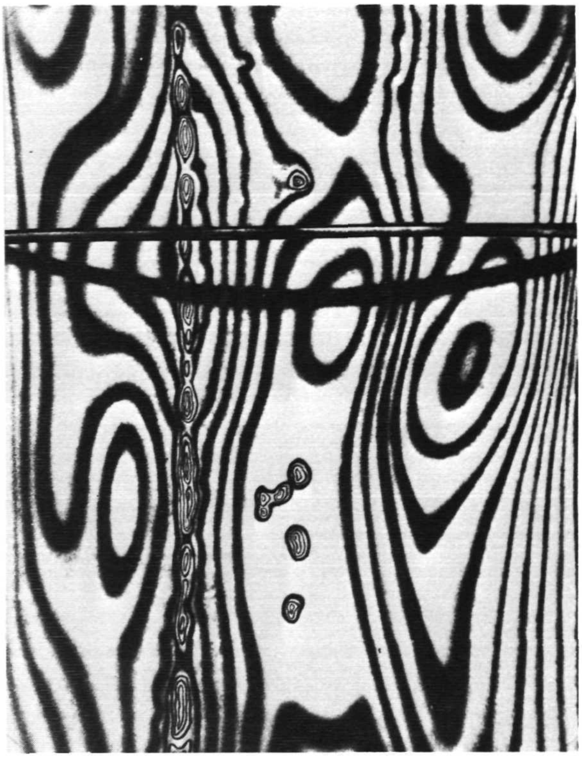


FIGURE 43.–Reconstructed hologram of suspect defects on tire.

in engine component performance that would prevent the assembled engine from performing properly or cause a premature component failure.

A reconstructed time-averaged interferogram of the original turbine blades designed for a certain jet engine (fig. 44) shows that the blades resonated in the lowest frequency or first bending mode at a frequency of 7986 Hz, just short of the requirement for this engine's component (8000 Hz without resonances). Three subsequent redesign efforts, characterized respectively as long chord, quick fix, and short chord, changed the modal characteristics and resonance frequencies (fig. 45). The quick fix and short chord adjustment successfully raised the first frequency bending mode out of the danger zone, while the initial long chord adjustment was unsuccessful.

Holography of this type is used on a routine basis to determine the need for redesign of various engine components such as jet burner cans, turbine blades, spray-bars, and inlet flaps. After design, all these components have passed their tests. The potential for this kind of testing is extremely promising. Pratt & Whitney is making plans to use computer assisted designs of prototype turbine blades. The computer input will be holographic fringe data from test photographs of the sample blade and equations of the blade's mechanical design and required performance. The output will be the necessary design changes for the blade. An objective for the future is to have the computer actually construct a digital hologram of the newly designed blade that could be used to reconstruct a three-dimensional image. Consideration is also being given to analysis of the fringe pattern photographs by microdensitometer for direct input into the computer (ref. 147).

Ball and Roller Bearing Transient Measurements

A very practical use of holography has been made by Naval researchers who used double-pulse, Q-switched, ruby laser holography to determine the nature and magnitude of minute deformations of ring ball bearings as they rotated about a loaded shaft. In precision rolling-contact bearings, a transient lockup and vibration of the balls or the bearing outer ring

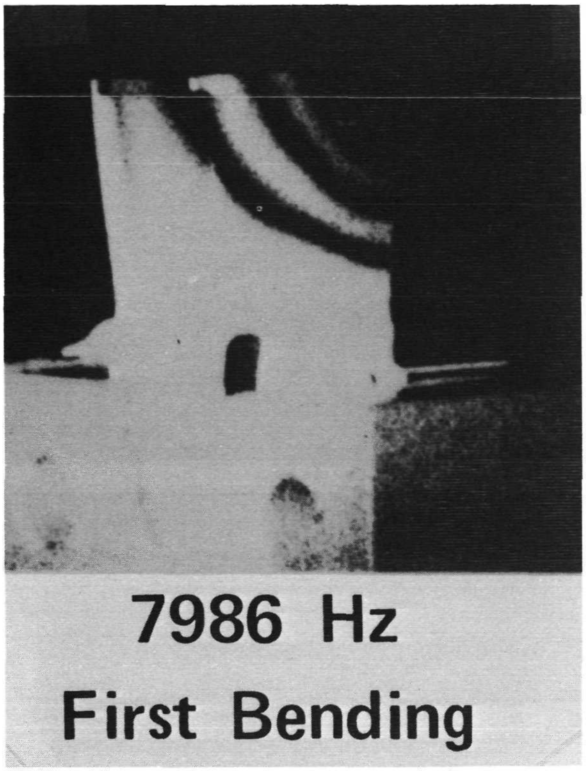


FIGURE 44.–Hologram of jet engine blade showing resonance in critical frequency region.

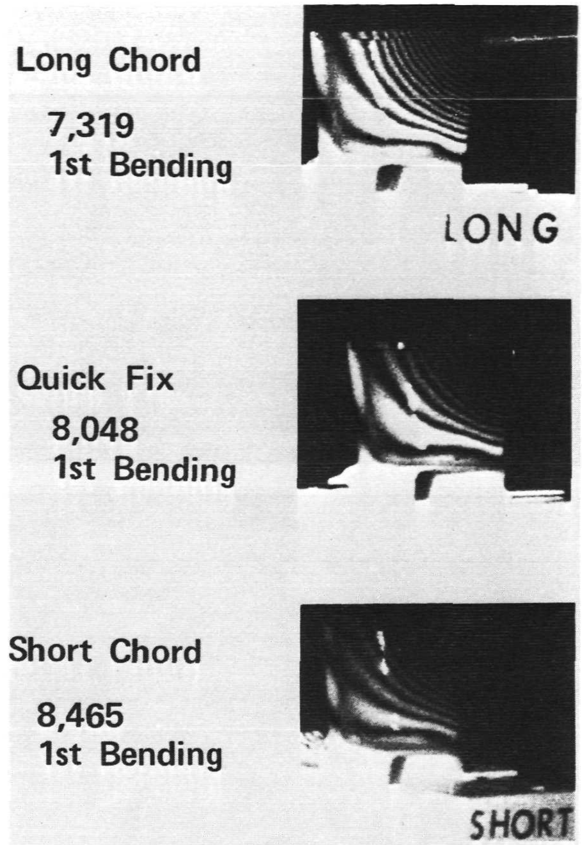


FIGURE 45.–Holograms of turbine blade after three redesigns: long chord, quick fix, and short chord.

frequency occurs just as the shaft begins to turn; the magnitude of these effects depends upon the type of lubricant used. It is vital to reduce these effects to a minimum, since they can transmit spurious vibrations to the rotating shafts and machinery and are believed to be the major cause of bearing housing oxidation and corrosion. Before this holographic technique was developed to make measurements at operating speeds, geometric changes in a bearing could be measured mechanically only when the bearing rotated at speeds considerably below normal operating conditions. Holography also seems to be useful in determining the symmetry of loading and misalignment of the ball bearings (ref. 148).

Pressure Transducer Investigation

The Babcock and Wilcox Co. (Alliance, Ohio) successfully used double exposure cw holography to aid in the construction and testing of a reliable diaphragm-type pressure transducer in which pressure deflects a diaphragm attached to a strain sensing element that generates an electrical output signal. The outer circumference of the diaphragm is bonded to the hollow base of the transducer, and proper operation of the transducer requires that this bond be stable and reproducible. Interferometric holography was used as a diagnostic tool to aid in development of a suitable bonding technique. It allowed measurements to be made of the mechanical deflection of the diaphragm. Although the electric output signal could have been used to analyze the bond characteristics, it was discarded because of expense and complexity (ref. 149).

Transportable Holographic and Fringe Control Systems

Various groups have been active in refining and standardizing holographic principles and equipment into compact packages, either portable or trans-

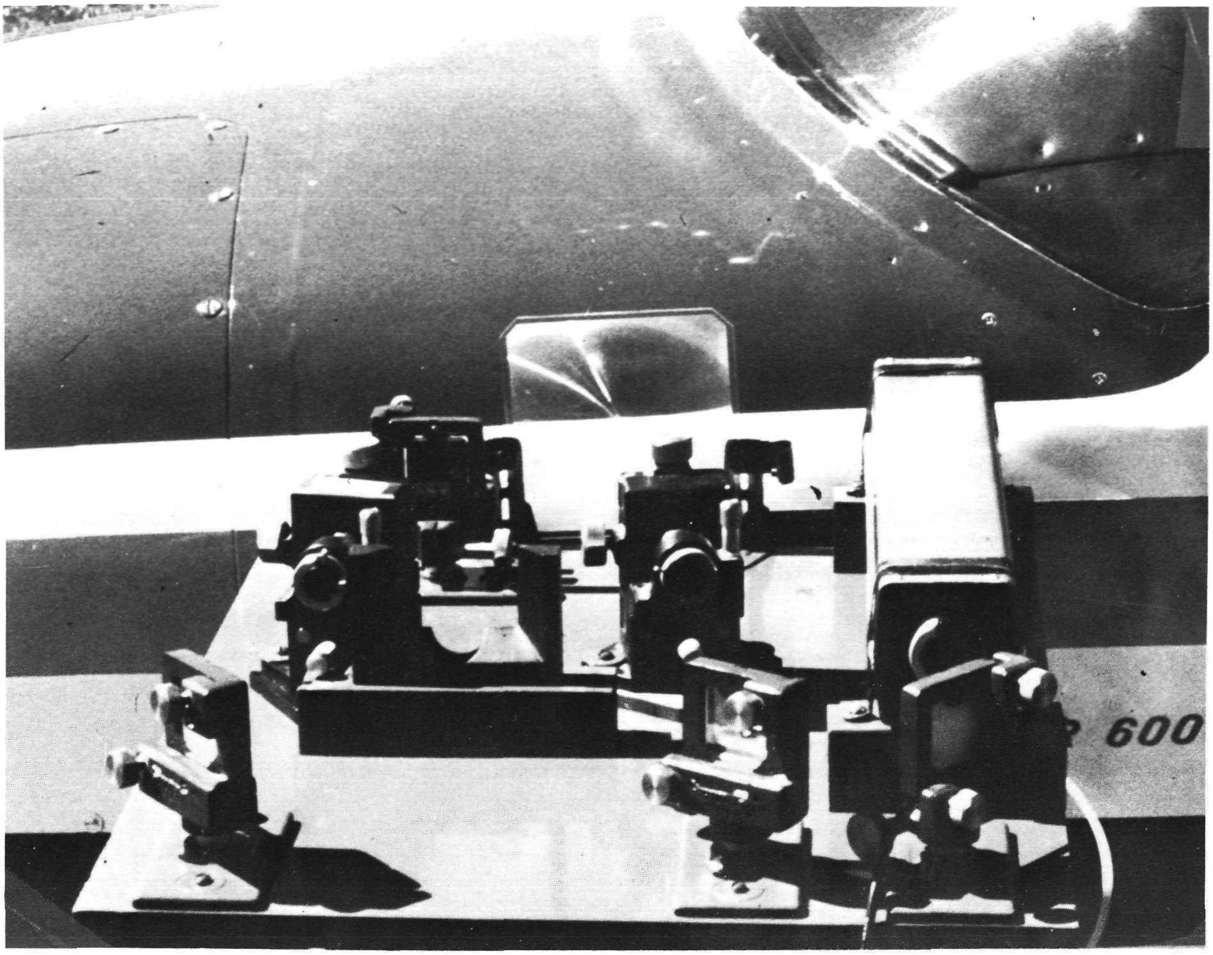


FIGURE 46.—Portable interferogram holocamera.

portable. A group at the Arnold Engineering Development Center has developed six operational systems for inline and off-axis holography that can be set up at various aerodynamic test and experimental facilities. Most of the systems use pulsed lasers in single- or double-exposure modes, either with a diffuser for three-dimensional display and interferometry or without a diffuser for Schlieren visualization, interferometry, or various types of spatial filtering. These systems provide the following types of routine testing data that are otherwise unobtainable (ref. 150):

- Vaporization and condensation phenomena in fuel tanks
- Material introduced into the wake of an aerodynamic model
- Analysis of droplet characteristics in simulated high altitude engine icing
- Dust characteristics in dust erosion facility
- Efficiency of particulate catchers in aerodynamic flows
- Rocket exhaust particulate measurement

E. Campaigne* developed for GCO, Inc., a compact cw holographic system designed to be strapped onto the system or component to be tested. An arrangement of this kind helps the holography of normally vibrating test objects, since the relative motion of vibration between the holocamera parts and the test object is minimized (fig. 46).

Normally, when a test object is stressed either thermally or by mechanical force, the entire object is

*Now with Radar and Optics Laboratory, University of Michigan

deformed and shows general fringe changes, but the weak areas show greater deformation. A novel feature of this holocamera is that the fringe pattern can be altered by changing the position of the reference source beam. It is therefore possible to shift the general fringe pattern caused by the general deformation to accentuate anomalies caused by a particular defect. Before the interferometric photograph in figure 47 was taken, two small points were center-punched on the front side; the fringes were then made to center on these slightly elevated points on the back side of a small steel plate (refs. 151 and 152).

Detection of Stress Corrosion Flaws and Cracks

Stress corrosion is the formation of small micro-cracks due to internal tension and corrosion of the specimen, without externally applied stress or loads. Holographic interferometry can detect such cracking processes early if they manifest themselves by displacing the surface of the test specimen. A set of holographic reflection interferograms (fig. 48a, b, c) shows the progression and growth of a stress corrosion induced crack in titanium alloy submerged in anhydrous methanol over a period of 14 hours. Initially this crack was not detectable visually (fig. 48a) (ref. 153).

The holographic interferogram in figure 49 shows a radial crack 3/16 in. long (at 12:00 o'clock) deliberately made by a coping saw. A much finer radial crack whose location and length can be detected only by discontinuities of slope in the fringe lines at about the 2:00 o'clock position from the pin is illustrated in figure 49b. These specimens were stressed by drawing a hardened bolt with a taperered shank into the hole, and a normal cw double exposure hologram was made of the undisturbed and stressed states of the specimens (ref. 152 and 153).

Modulated Reference Beam Holography

The discovery of C. Aleksoff and his colleagues at the University of Michigan may be the most significant breakthrough since the first time-averaged hologram was made by Haines and Hinderbrand. Basically

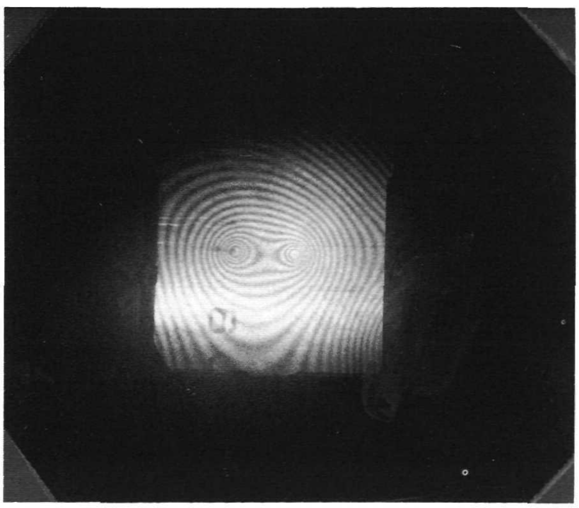


FIGURE 47.–Holographic fringe control.

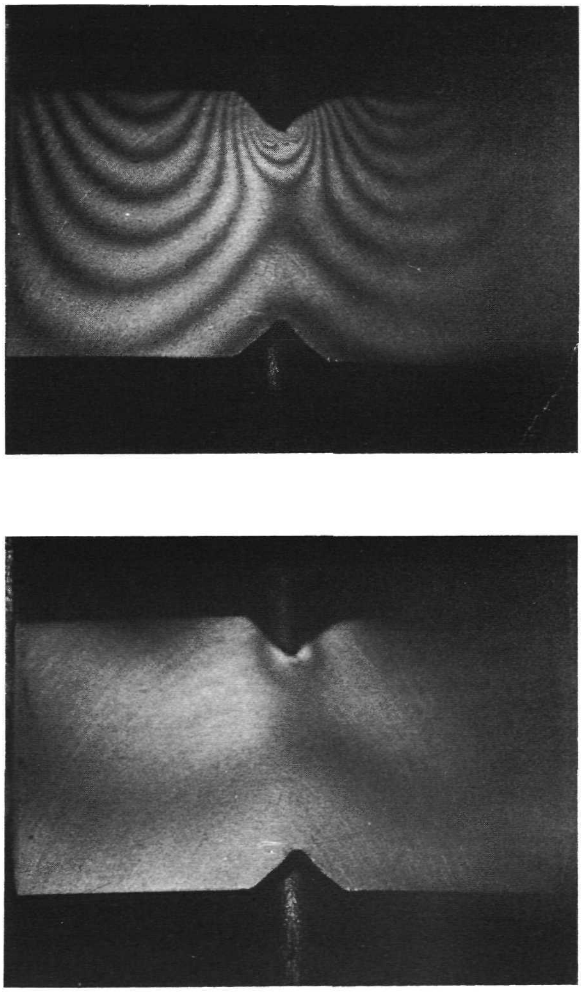


FIGURE 48.–Stress corrosion crack holography.

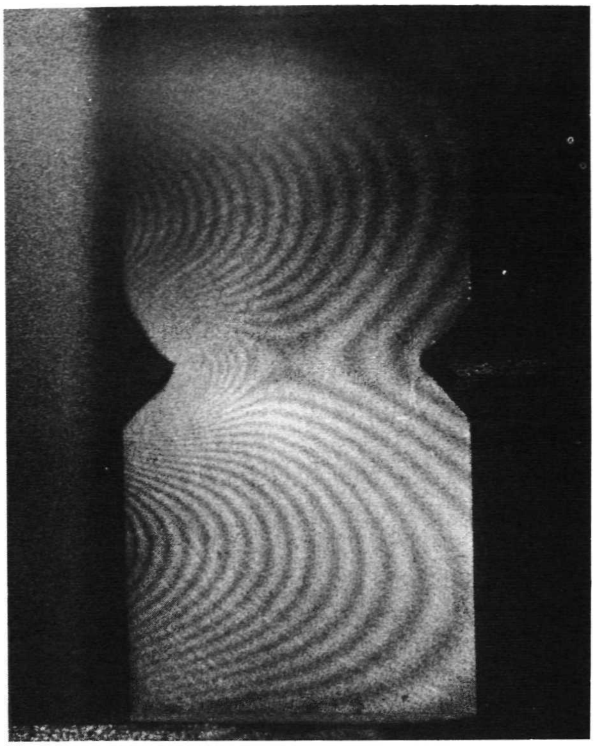


FIGURE 48.–Stress corrosion crack holography–concluded.

Aleksoff found that if the reference beam is shifted in frequency by an amount equal to the mechanical exciting frequency of the subject, or by its nth harmonic, then the shapes of the time-averaged contrast contour curves (fig. 35) can be dramatically adjusted. The implementation and extrapolations of this technique are far-reaching; in fact, its ramifications have already affected such areas as acoustic holography and holographic data processing, as well as holographic interferometry.

The change in the shape of these contrast curves has practical value. One application is illustrated for time-averaged vibrations of a speaker cone (fig. 50). These photographs show the differences between normal time-averaged holography (no frequency shift of the reference wave) and 75th order reference beam modulation holography (frequency shift of reference wave in an amount equal to 75 times the subject vibrational frequency). A normal time-averaged hologram of a speaker being driven very hard makes it impossible to determine what order of fringe the center part of the speaker is generating (fig. 50a). However, the second hologram of the same speaker vibration, using reference beam modulation, (fig. 50b) shows that the center part of the speaker is contributing to the brightest fringe.

Modulated reference beam holography permits large amplitude vibrations to be faithfully mapped as fringe contours, and can equally well map extremely small amplitudes down to the order of 1/100 of a wavelength of light. The reference beam modulation is shifted only by the exciting frequency for this purpose. Modifications of this technique may also be used for reconstruction of ultrasonic beams, optimization of reference to object wave intensity ratios, fringe synthesis, frequency and phase modulation of object waves, shutter modulation of both object and reference waves, and periodic modulation of both object and reference waves, either at the same frequencies or at frequencies with periods that are rationally or irrationally related to each other (ref. 154).

Summary

The types of holography discussed above have begun to move the science of optical interferometry out of the laboratory and into the test facility, the field test site, and occasionally even the production line. Yet holography has done more, for while interferometry can measure displacements to fractions of a wavelength, evaluation of just what measurement was being made and where it was being measured has been a major problem.

Interferometric measurements are notoriously delicate and unstable, but holography has changed this. Now, superimposed upon the photograph of an object being examined, an engineer or scientist may have a recorded contour of interferometric changes that are the result of known conditions at the time the hologram exposures were made. Since the fringes of the double or time-averaged hologram are essentially differential, imperfections in any part of the system that do not change are eliminated. These include imperfections that have been problem areas—the roughness of the glass walls of a test chamber, the relatively crude quality of auxiliary optics, film emulsion irregularities, etc.

These considerations make interferometric holography seem like the layman's interferometer. Unfortunately current practice of this technique is not without its limitations.

Any component of a holographic system, be it a loose optical element, a vibrating plate holder, or any

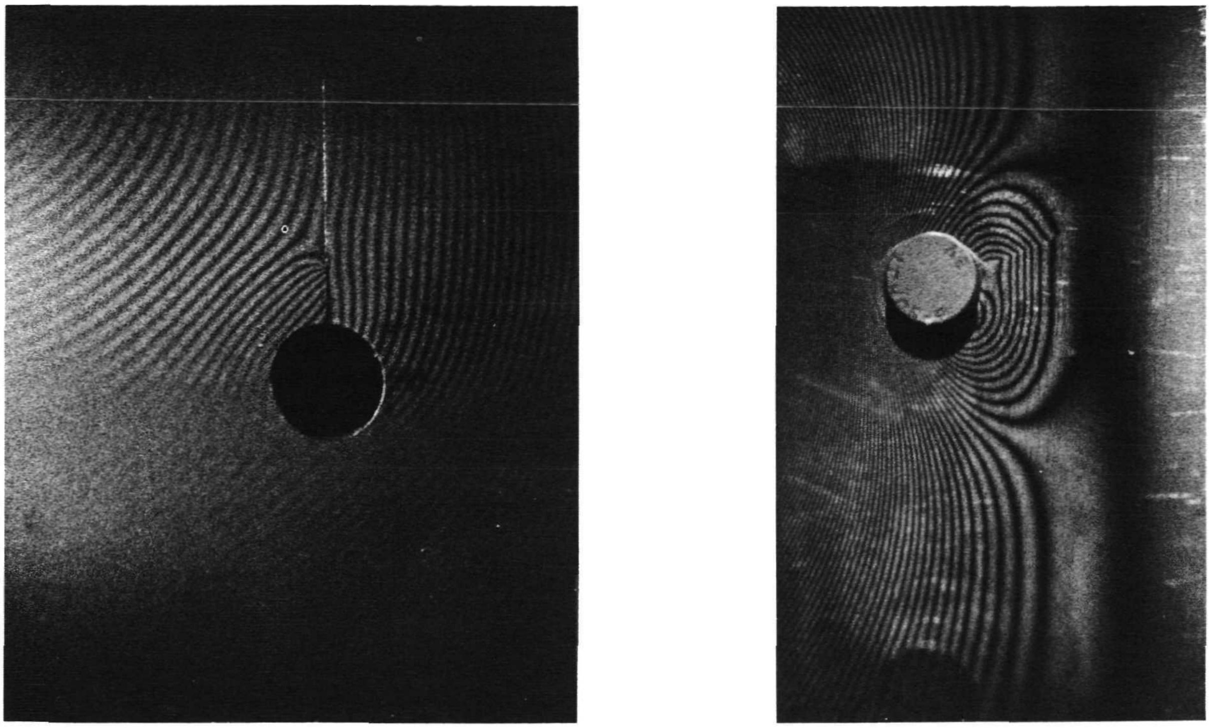


FIGURE 49.–Holographic crack detection.

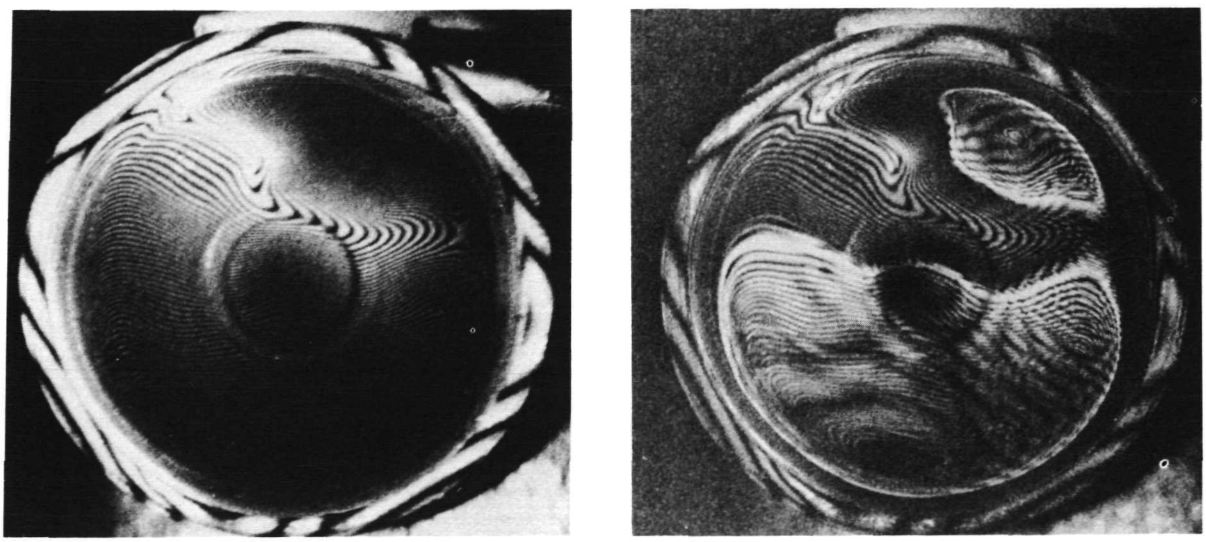


FIGURE 50.–Reference beam modulation holography of speaker cone.

movement of the object to be inspected, contributes its bit to the differential hologram. Its effect must therefore be correctly compensated for, or false conclusions will be made about the subject and its flaws and defects. Second, the sensitivity of the process to displacement is inflexible and cannot be adjusted. This can result in any of the following conditions:

Only very small stress and resultant strains can be recorded.

Anomalies are displayed that may be insignificant influence on practical performance and design.

The wave disturbances caused by the stress interactions are not great enough to examine thin samples.

Third, only flaws, defects, or changes that are contained within material transmissive to the object beam can be seen and measured. This and the other two characteristics contribute to the fourth and greatest problem: correct interpretation of the results. The final report depends on knowledgeable interpretations, and these in turn depend on the interpreter's ability.

The engineer most familiar with a test component, process, or method may be the best qualified to start holographic interferometric experimentation, after some orientation and training in holography. He must investigate ways to keep unwanted vibrations to a minimum, the best geometry, and the type of exposure (interval and length) to use; he must also determine what exciting forces and frequencies or stresses to use on the subject. Under these conditions holographic interferometry can be of value in many applications.

CHAPTER 7

Motion Picture and Television Holography

The type of holography that people will observe most directly is the eventual use of three-dimensional images for entertainment and education. Such images may someday be formed in a theater or possibly transmitted by microwave or telephone lines onto television and projection screens in homes and offices. These applications on a mass scale are still in the future, although small-audience holographic motion pictures now appear feasible. A less dramatic but significant use of holographic three-dimensional motion pictures will be as an aid in research and development. Motion pictures of the holographic interaction fringes caused by tiny displacements of a moving subject will also be discussed in this chapter.

Since viewing a hologram is like observing a scene through a window, the larger the hologram or "window," the greater the number of observers who can simultaneously view it. Motion picture holography for public viewing has been limited because of this inherent drawback: Hologram film is very small. Scientists and optical engineers speak of this problem as a need to reduce the information content required on the hologram and yet be able to reconstruct an image of acceptable quality. This reduction is also necessary to make three-dimensional television picture transmission practical.

NASA RESEARCH AND DEVELOPMENT

Reducing the information content of holograms was one of the first problems investigated by University of Michigan researchers under a NASA grant. This study led to the development of one of the earliest motion picture hologram systems. The researchers first verified that a dispersion method yielded the best tradeoffs between the information content, perspective field-of-view, reconstructed image resolution, and signal-to-noise ratio of the reconstructed image.

Brumm and Haines discovered that if ground glass was used for the dispersion medium (scattering plate) (fig. 51) the image became excessively "noisy" as hologram size was reduced, although image resolution remained relatively constant. A special type of diffraction mask was then developed as a scattering plate. The mask produced a fairly noiseless reconstructed image whose resolution decreased as the size of the hologram was reduced (fig. 52). This discovery became the basis of a very primitive system for projecting true holographic motion pictures. The apparatus (fig. 53) recorded image frames on specially prepared flat plates (ref. 155 and 156).

Building on this early advance by the University of Michigan, a number of other developers are now experimenting with motion picture holography. Jacobson and his associates at Hughes Aircraft Corporation have independently recorded and projected holographic motion pictures of fish swimming in a tank. Back lighting was used to display the developed film, so that the viewer could see the real image. The results were quite good and showed the fish swimming in space.

The only difficulty encountered was a jitter problem due to inadequate synchronization between the rotating shutter and the camera film advance. In a number of frames, the film was moving while

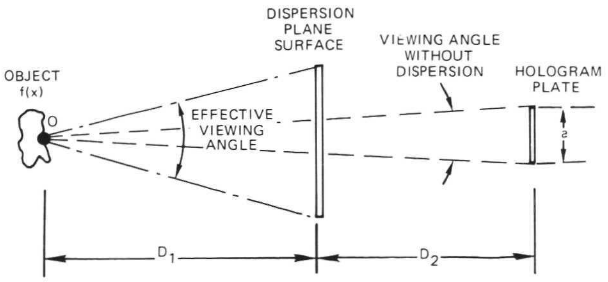


FIGURE 51.–Construction of a hologram through a dispersion plane.

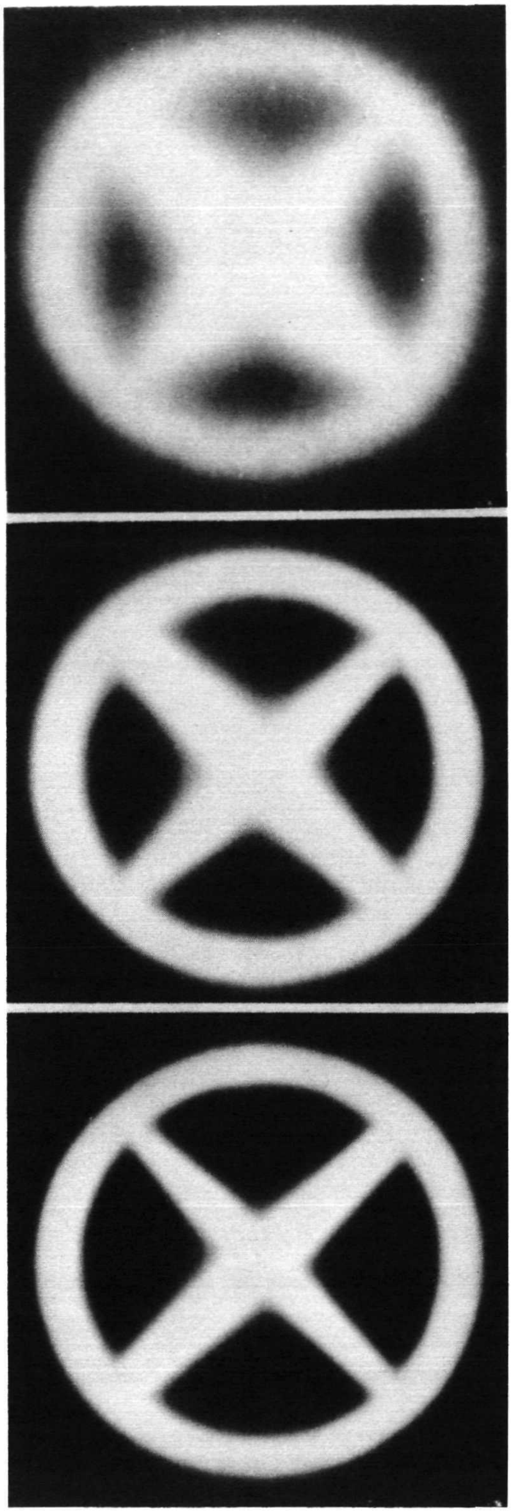


FIGURE 52.–Imaging through a resolution reducing dispersion medium.

FIGURE 53.–Scanning disc assembly for producing animated hologram movies.

exposure was in process. This problem can be resolved by improving the synchronization between the shutter and film advance mechanism or by using Fourier transform hologram frames much less sensitive to film motion (ch. 3, app. B).

As a result of this experiment, Hughes researchers think that the most promising applications of this technique will be found in picture holomicroscopy, time-resolved holographic interferometry, and time-resolved particle dynamics studies (ref. 157).

Motion pictures of holographic images have been taken or proposed for several NASA applications. High speed motion pictures have been made of the transient responses of a vibrating beam, cylinder, and disk, and the responses were correlated with mechanical theory and calculated displacements. These experimental results have not yet been applied to practical problems (refs. 111 and 113).

Figure 54 shows the fringe patterns generated by the transient motion of the cylinder after it was struck by a ballistic pendulum. The frames show both the real-time fringes produced by the transient motion and its eventual decay with time. This series was photographed at 5000 frames per second.

Frame 1 in the figure is the fringe pattern seen before the shock. This complex fringe system before

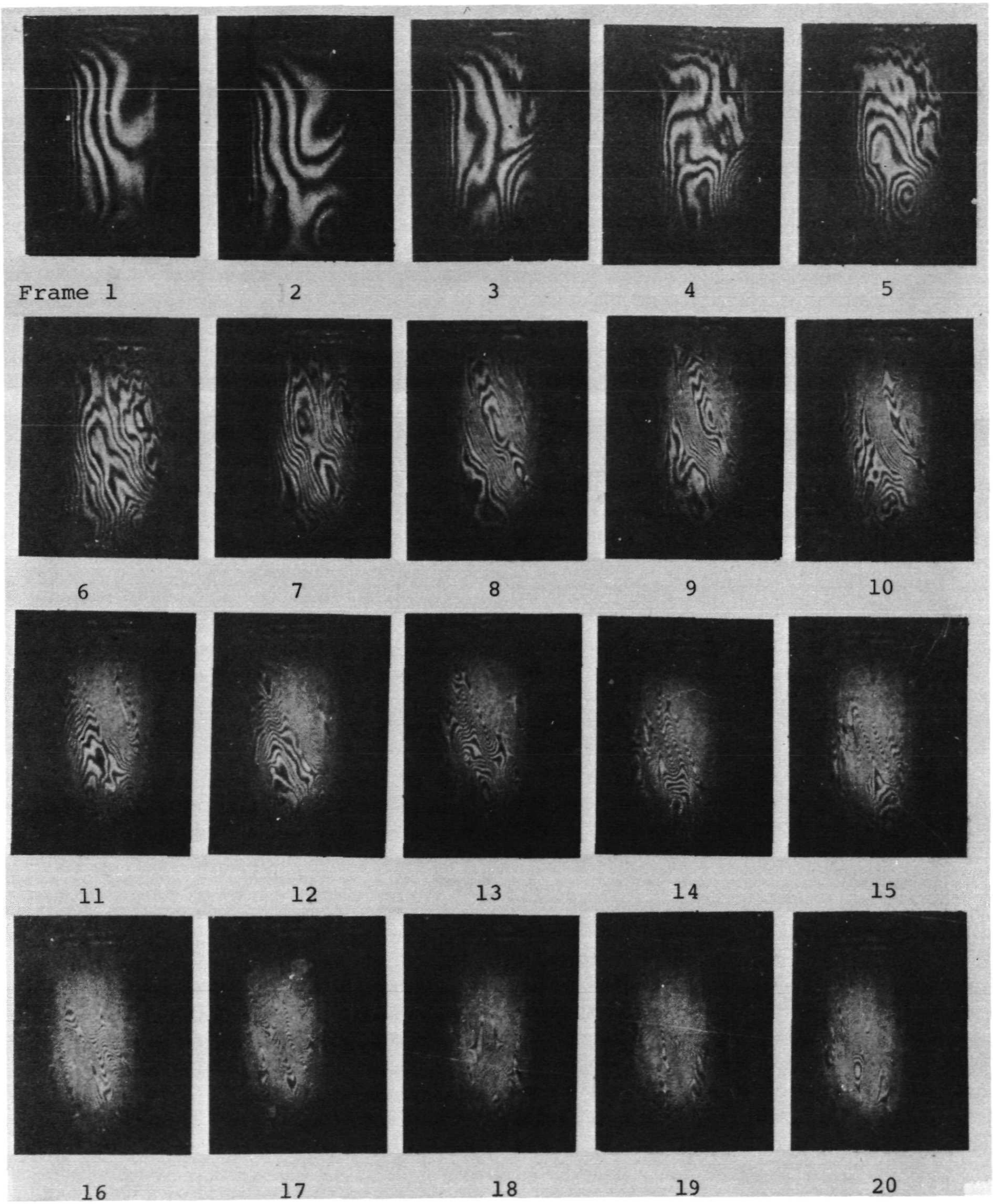


FIGURE 54.–Real-time holographic interferometric fringe system of 18-inch-diameter cyclinder photographed by high-speed camera (5000 pictures per second) after shock event (frame 2).

shock was caused by the object's holographically noticeable contraction and expansion with very small temperature changes. The problem was so acute that even opening of the door of the laboratory caused a noticeable fringe shift; later tests with the transient response of the disk were hindered even by vibration of the hologram plate caused by camera noise.

Difficulties encountered in these experiments can be overcome in the future by maintaining closer temperature control of the working area, isolating the holographic system from the operator and from heat generating instruments, reducing noise vibrations of the camera, and greatly increasing the sampling rate. It seems possible that quantitative analysis of the fringe movements corresponding to transient responses of cylinders, disks, and plates can thus be accomplished (ref. 119).

A promising new technique developed by R. Kurtz of MSFC for making real-time three-dimensional motion pictures is based on the concept of taking simultaneous back and front light holograms of rapidly moving objects in an ellipsoidal configuration (ch. 3). This concept may be implemented in several different ways (one is shown in fig. 55); all are covered by patent applications. Not only can sequential holograms of a high speed object be recorded, but as many as 10 separate holograms can be recorded on the same small area of film (ref. 158). According to Kurtz, the potential usefulness of real-time motion picture holography is virtually unlimited. He believes it may provide a dramatic increase of usefulness over regular stationary holography, just as the two-dimensional motion picture was a great advance over still photography.

Utilizing one of the patented methods mentioned above, R. Kurtz and L. Perry of MSFC's Space Sciences Lab recently provided the first demonstration of a true three-dimensional motion picture camera with front surface resolution of detail from a moving object. A 100-ft roll of 70-mm film was successfully used to record the constant motion of a moving target in real time with a cw laser and the image reconstructed resolution of front surface detail.

Kurtz plans to use holographic real-time motion pictures to monitor the thin film particulate and contamination buildup on optics elements and components in space (ch. 6). Other non-NASA researchers have also been pursuing means of recording holographic motion pictures or sequences of holograms of extremely rapid events. Carpluk at the University of California is working on a stereo laser framing camera. The Institut Franco-Allemand de Recherches is investigating holography of moving phase objects, and A. N. Zaidel of the Soviet Union has obtained a sequence of holographic frames only 40 nanoseconds apart (refs. 159 through 161).

COMMERCIAL ENDEAVORS

D. Gabor is pursuing the development of commercially oriented, three-dimensional holographic films that can be projected in a theater and do not require the viewer to wear special glasses. The system uses a special screen assembled with segmented lenticular-like surfaces of a photosensitive material mounted in a hollow curve called a "holographic mirror" that reflects to all parts of the theater. Two lasers project separate holographic pictures for each eye. The screen reflects the images in interleaved vertical zones, each the width of normal eye spacing and these dual images are combined instinctively by the eye to produce the stereoscopic effect.

The Gabor technique significantly increases the versatility of holographic filming, because the film can be made with a conventional stereoscopic camera using conventional lighting rather than the lasers usually required for holograms. Lasers are used only to project the stereoimages onto the holographic mirror. Although Gabor's investigations do not yet have the large-scale financial backing required for actual commercial development, a German corporation has shown interest in acquiring rights to produce films using his patented method (refs. 162 through 165).

Some interest has also been shown in commercial filming of laser-illuminated holographic motion pictures. Joseph Strick, a motion picture producer, has announced his intention of making a holographic movie based on a patented method. Budgeting for the film has been set at $1 million, with an additional $400 000 for equipment. All filming will be done in studios using laser lighting.

North American Philips Laboratory has been experimenting with bandwidth reduction and holographic films and has announced establishment of a holographic movie "studio." TRW has also been making sequential holograms of various scientific phenomena (refs. 165 through 167).

At present, holographic television does not appear feasible due to the large transmission bandwidth

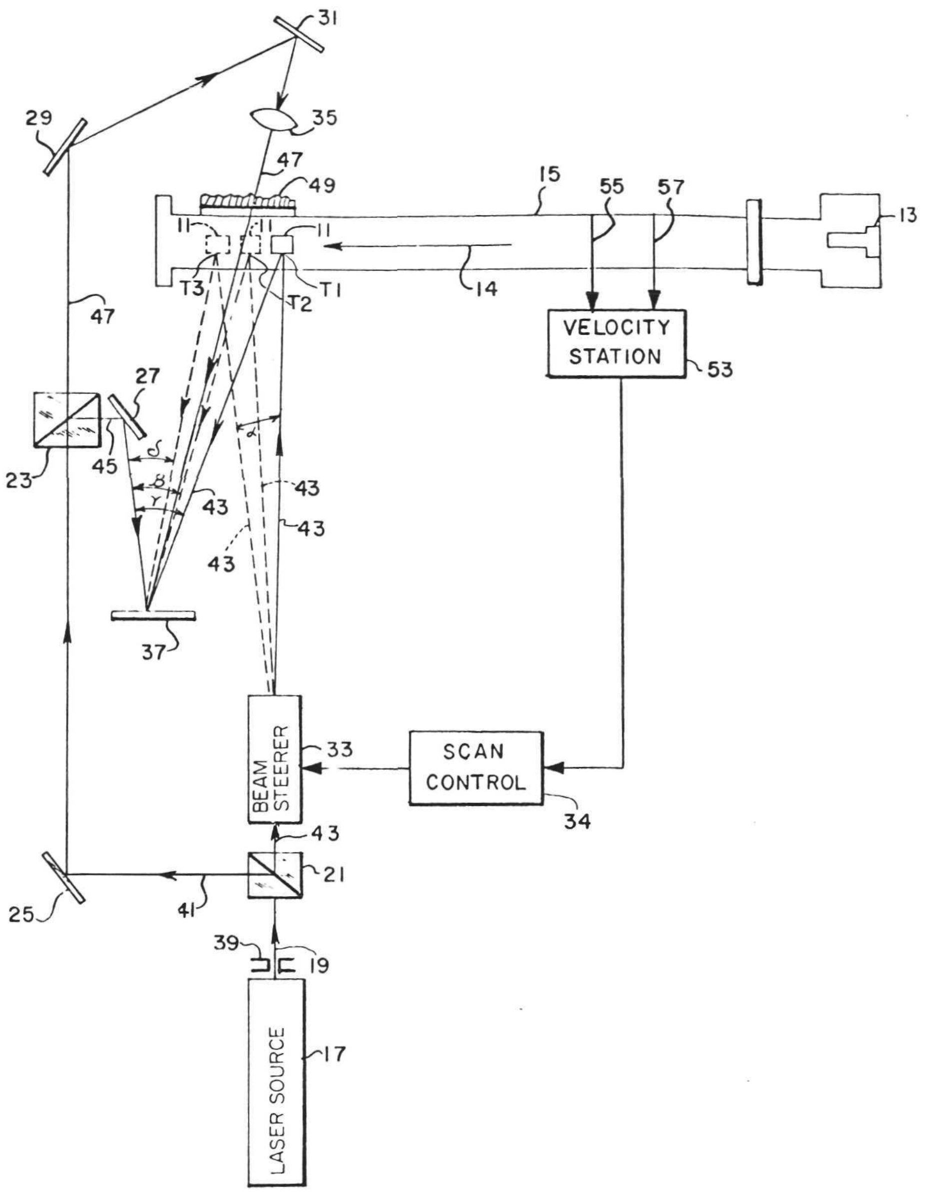


FIGURE 55.–Cine-holography of high-velocity objects.

requirement. In a recent article, Gabor, et al., pointed out that 90 billion dots of information would be required to transmit a single holographic TV picture frame. This is based on a resolution requirement of 1500 fringes/mm and an 8-in. square picture. A television frame in the United States presently carries only 250 000 dots of information. Some of the progress in reducing bandwidth and information content required in holographic movies, however, can be expected to have a direct impact on holographic television. For example the scatter plate technique developed by Brumm and Haines at the University of Michigan and the horizontal strip technique of DeBitello both reduce bandwidth requirements; and Bell Telephone Laboratories have been investigating the transmission of holograms using narrowband video signals. All these projects have so far been experimental, but holographic picture phone communication may be a possibility (refs. 164 and 168 through 171).

CHAPTER 8

Nonoptical Holography

Although nonoptical holography has lagged somewhat behind the development of optical holography, interest and research are increasing in this area. Few materials are transparent to light, but almost all are partially or fully transparent to microwaves, acoustic waves, or seismic waves. Thus while optical holography is best suited for studying surfaces, nonoptical holography is valuable in probing the interior of substances, equipment, or living matter. Nevertheless, as previous chapters have shown, holographic study of even the surfaces of thin objects can reveal a surprising amount of information about defects, imperfections, or failures in their interiors. Testing and measurement by nonoptical holography supplement rather than replace optical holography.

Nonoptical holograms are formed on the same basis as optical holograms. They also require an object, an object beam illuminator or transducer, a reference beam illuminator or transducer, and a sensitive recording layer or array of point detectors to act as the hologram. Because most nonoptical detectors can directly record both the amplitude and phase of the object wave, the reference beam and its illuminator can sometimes be eliminated.

Acoustic holography requires the object and source transducers to be immersed in a tank of water as the best and most convenient transmitting medium. In conventional acoustic holography, the detector array is often replaced by the water surface of the test tank. However, working with these waves generally requires specialized, bulky, and expensive equipment, which is one reason for the slow development of this kind of holography. Nonoptical techniques also require specialized experience; interpretation of distorted holograms formed by passage of waves through the transmissive object is a complex task.

The synthetic aperture, sidelooking radar (a form of microwave holographic radar) and the acousto-optical holographic image system are the only items sufficiently developed to have commercial importance. Others are still in the research and development stage, and are not yet ready for practical application. Synthetic aperture radar has been used extensively for several years in military surveillance and mapping and now is being applied to earth resource surveillance and management. Acoustic holography has recently emerged in the industrial world and appears ideally suited for inspecting and testing the interiors of all sorts of materials, equipment, and organisms; new uses are continually being found in medicine and manufacturing.

Application of holographic techniques to seismology is at the early exploratory stage. The principles and characteristics are similar to those of acoustical holography extended to the very low frequency regions, but with some key differences. The long seismic wavelengths require large recording areas, and the seismic "synthetic aperture" method seems to be the best approach for recording the wavefront.

A number of different sources have been used for seismically illuminating the area to be studied. Mechanical vibrators, impulses, and even an explosive charge have been used. With the explosive charge, only components of a single frequency were used in constructing the hologram.

Again, the formidable part of seismic holography is the interpretation of results. Inhomogeneities of the earth as well as the structural inhomogeneities of individual formations themselves distort the seismic and sound waves in a very complex fashion. The resulting holograms appear meaningless under normal inspection. In this area, however, as was the case with pulse-echo seismic mapping, progress in data processing will make it possible to extract valuable information from the holograms. Once available, seismic holography may be a valuable tool for oil and mineral exploration, subterranean water detection, local fault detection, and geological exploration (ref. 172).

NASA RESEARCH AND DEVELOPMENT

Some of the nonoptical holographic research efforts of NASA have concerned the following areas:

- Nondestructive testing and defect detection by microwave holography
- Microwave holographic contour generation
- Recording of microwave holograms
- Temporal reference acoustical holography
- Direct acousto-optical wavefront reconstruction
- Electronic sound holograms

Two developments that show considerable promise are nondestructive testing and inspection using microwaves, and generation of terrain relief and contour maps using a special type of holographic microwave system. NASA is vigorously supporting development work on both of these systems, but several problems must be solved before they can have commercial value. For example certain image aberrations now present in terrain relief and contour mapping need to be reduced so that better maps can be made at higher altitudes. Plans have been made to use dual microwave frequencies to map out ranging terrain contours automatically. A study is also in progress on possible direct recording of microwaves on film, which would greatly simplify the recording of microwave holograms.

The usefulness of microwave holography in producing and processing radar signals is established, but few applications for microwaves in nondestructive testing have yet been devised. The resolution of the current microwave defect inspection system needs to be increased and the scan modified to give full three-dimensional images instead of two-dimensional cross-section views.

Defect Detection by Microwave Holography

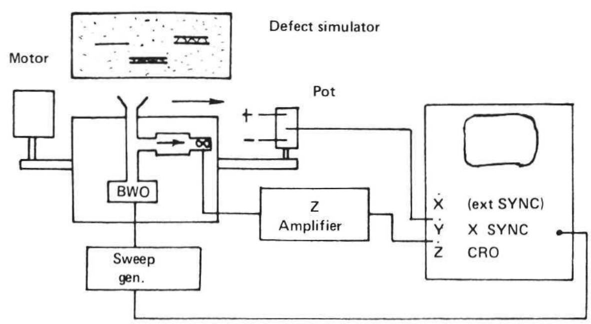
A microwave holographic system is being developed for JPL to allow inspection of a solid propellant motor. The three techniques tested to date are based on conventional types of radar dimensional scans. One of the scans (the "A" scan) was one-dimensional in depth only; another was two-dimensional in depth and along the horizontal at a given height. The "A" scan tested optical processing of a new type of radar known as a "frequency domain interferometer" (FDI) suitable for depth resolution at very short minimum ranges down to inches or less. It was developed by Electro-Physics under a NASA contract.

The basic method of operation is to sweep the frequency of the transmitter probe, so that at any scan position the frequency returned indicates the range at which that signal was reflected back. There is an apparatus for two-dimensional scan in depth and along a horizontal axis (fig. 56a). Figure 56b shows the concept for reconstruction. The resulting hologram is in the horizontal direction only (representing depth) and is a recording of the frequency domain interferometer (FDI) signal.

The results of these experiments are encouraging, and the developer believes they indicate the feasibility of a sidelooking radar based on the FDI principle for nondestructive testing and possibly ultrasonic inspection (ref. 173). Production of full three-dimensional images requires further development (refs. 173 and 174).

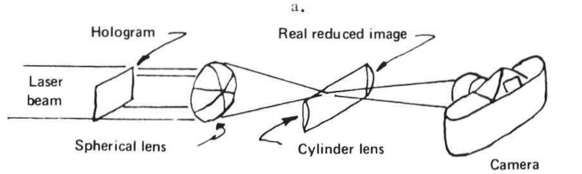
Microwave Holographic Contour Generation

For MSC, the University of Michigan's Institute of Science and Technology is planning to investigate use of holographic techniques to map terrain contours from an aircraft. Mapping of this type could be



Recording B–Scan hologram with FDI

a.



Reconstructing B–Scan image

b.

FIGURE 56.–Frequency domain holographic interferometry.

readily correlated with infrared and other optical mapping techniques, because the holographic technique works best from directly below the aircraft out to an angle of about 45 degrees from the nadir, the same angles of coverage over which optical scanners work best. Sidelooking radars map better at coverage angles from about 20 to 75 degrees. Contours are formed in the range dimension in the same way as optical contours are made (ch. 6).

Equally good resolution in the cross-track direction is obtained with conventional phase array radar, also a form of microwave holography. Dr. R. W. Larson of the University of Michigan has built a feasibility model of a contouring radar that produced mappings with 20-ft ranging contours in the flight path direction using the holographic technique. Phased array techniques were required to achieve a 20-ft matching cross path resolution. It was limited in power to a maximum altitude of 1000 ft and maximum slant angle of 45 degrees, giving a 2000 ft by 2000 ft coverage pattern.

The top of figure 57 shows a picture taken by this radar model of terrain whose contour is shown at the bottom. Note that at far ranges and large slant angles from the nadir the range contours naturally tend to be compressed, making interpretation difficult. This problem will be investigated further under NASA contract (ref. 175).

Recording of Microwave Holograms

One of the difficulties in microwave holography, as in all forms of nonoptical holography, lies in recording the wavefront. The usual procedure has been to use horn antennas to mechanically scan the electromagnetic field. The recorded field is then electronically processed and displayed on a cathode ray tube (CRT) device, which is photographed to establish a permanent record. This procedure is also used with acoustic holography.

Under a NASA grant, research at Harvard University has produced interesting results in direct microwave recording. Polaroid film is exposed to an electromagnetic field which generates a thermal image that causes the film to develop selectively. A crude microwave hologram can thus be made directly, just by exposing the film to the field to be recorded. K. Iizuka has expanded this research using an illuminating microwave field in an interferometric setup (refs. 176 through 178).

Acoustic Holography

Holograms in the acoustic wave range of 30 kHz to 10 GHz can be useful for a variety of purposes, from oceanography at the low end of the spectrum to ultrasonic microscopy at the high end. Within the mid-range lie the promising applications of nondestructive testing and medical diagnosis. For some time NASA has been investigating methods of reconstructing the acoustic image directly from acousto-optical interaction, without the need to form an acoustic hologram. Hopefully such techniques will eliminate aberrations, increase sensitivity, and speed up the reconstruction process.

Considerable experimental work is continuing on the use of acoustic energy to form holograms in highly sensitive areas and organs of the body; these techniques could greatly improve medical diagnosis and treatment. Possibilities also exist for inspecting

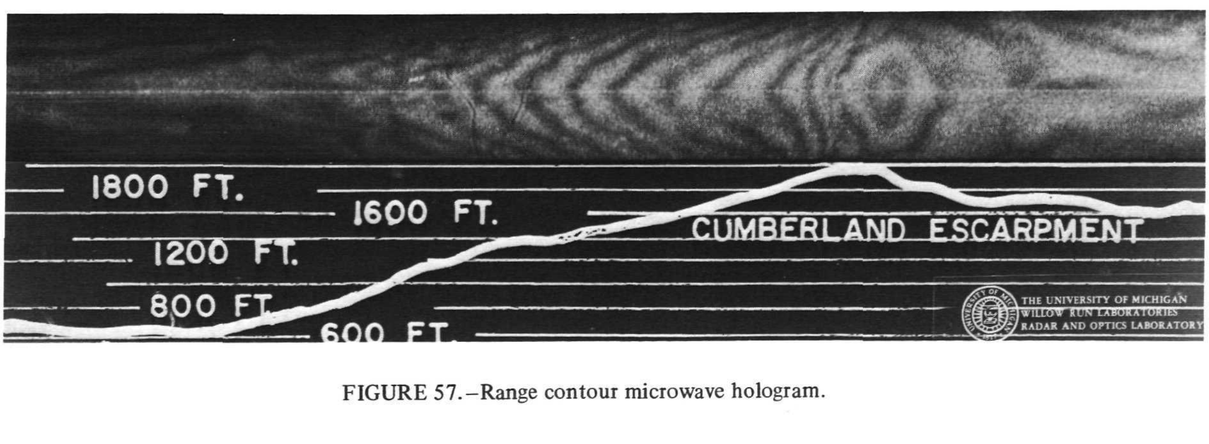


FIGURE 57.–Range contour microwave hologram.

perishable foods with either acoustical waves or microwaves.

Temporal Reference Acoustic Holography

McDonnell-Douglas studied the application of acoustical holography to medical diagnosis for ERC. The objective was to find a noninvasive three-dimensional recording method for visualizing soft tissue structures without harmful radiation.

The investigators first reviewed the nonholographic pulse-echo imaging techniques presently in wide clinical use. Although they provide valuable information, image quality is poor and repeatability is low; these problems caused Queen's University to abandon the technique in brain tumor research. As a result, McDonnell-Douglas investigated two approaches to "temporal reference acoustical holography."

One approach involved the direct recording of an acoustic wavefront, as shown in figure 58. Since the wavefront amplitude and phase are instantaneously captured, no reference beam is required as in conventional liquid-surface holography. A "Sokolov ultrasound camera" is used to record the wavefront. The results of this experiment were not as good as anticipated, however, because of imperfections in the setup and the interaction characteristics of the ultrasound camera.

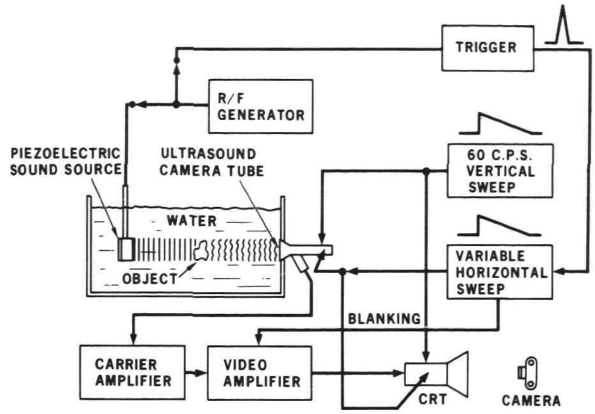


FIGURE 58.–Ultrasonic camera system producing the non-time-averaged temporal reference holograms.

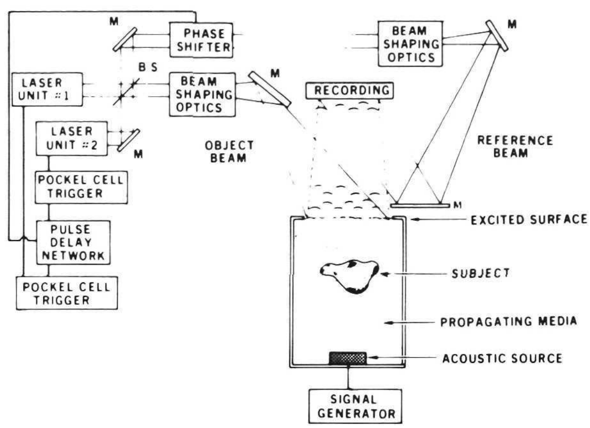


FIGURE 59.–Schematic of double pulse holography system to record temporal reference holograms.

McDonnell-Douglas' second detection and recording scheme is a new form of surface layer acoustic holography (fig. 59). Instead of making a hologram of the steady-state standing wave generated on the surface, as in commercial units, the system makes a differential double-exposure interference hologram of the surface at two separate controlled times. The interval and spacing between the two exposures is timed so that the second exposure is made half an acoustic cycle after the first (hence, "temporal reference" holography). Results with this system have been favorable (ref. 179).

Direct Acousto-Optical Wavefront Reconstruction

JPL has been supporting TRW in researching methods to reconstruct the optical image directly from acoustic waves transmitted through various types of object specimens. This would eliminate the need to form an acoustic hologram and would simplify the subsequent problem of recording and later reading it out for final reconstruction. Current use of the surface interaction wave solves part of this problem, since the surface itself is the acoustic hologram, but TRW has carried this principle further.

Recent TRW work is based on the Bragg diffraction method used extensively for acousto-optical laser beam deflection (ch. 9) where the sound wave functions as a diffraction grating to the laser beam (ref. 180). This method has been used for nondestructive testing of solid propellant, elastomeric materials such as neoprene, which highly attenuate frequencies in the 100-MHz region (refs. 180 and 181).

Electronic Sound Hologram

Similar efforts have been planned at LRC. An acoustic holographic facility will be used to locate

and measure flaws, fatigue induced cracks, bonds in composites, etc. (ref. 182). The equipment at this facility will be designed so that "one could inspect the interior of an object without going through the intermediate step of developing a hologram. Such a scheme would permit a real-time inspection of internal flaws in much the same manner as with the use of acousto-optical holographic techniques. A possible implementation of this setup might be an "electronic sound hologram."

Other research is being carried out in direct reconstruction of acoustic holograms that may allow coherent acoustic processing very similar to optical data processing (ch. 9). It may also be possible to implement an acoustic interferometric inspection system that compares, for example, production samples with an established standard in real time (refs. 180, 183, and 184).

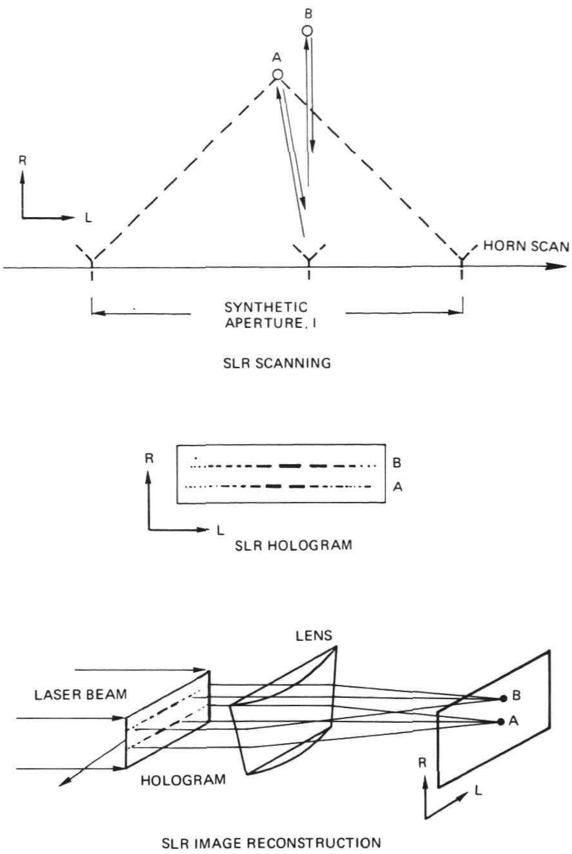


FIGURE 60.–Sidelooking radar holographic principle.

COMMERCIAL ENDEAVORS

Microwave Holographic Radar

In a sense, the first practical and commercial application of microwave holography was the "synthetic aperture" sidelooking radar. Microwave holography has benefited from the development of radar systems although they, of course, evolved quite independently of holographic considerations and were developed along information theory lines. However, hindsight shows not only that these systems can be considered holographic in nature, but also that considerable new insight is obtained when they are viewed as holographic processes.

Four common types of radar systems can be analyzed on the basis of holography:

- Synthetic aperture radar
- Chirp radar
- Rotating-target imaging
- Phased-array beam forming

Recording azimuth information on a synthetic aperture, sidelooking radar is a one-dimensional holographic process. Instead of recording the energy from a radiating point on a giant holographic plate held up in the sky, the recording detector (receiver on the aircraft) is scanned across the sky while the same point is being illuminated by the broad azimuth beam of the antenna. This is illustrated in figure 60. The top portion shows reflected radiation from only two points at different ranges and azimuths. The two points are sorted out in range by pulse time while they spread their radiation out in the azimuthal direction and the receiver scans over the length interval I. The laser beam reconstruction process shown at the bottom of the figure integrates the azimuthal data, over the interval I, for each point back into the correctly focused positions (refs. 174 and 185).

Holographic Microwave Gun Detection

The University of Pennsylvania's Moore School of Electrical Engineering has been working on a microwave holographic system for gun detection. Since only phase information is used, the final recorded image is termed a "phasigram" rather than a hologram (which normally would also contain amplitude information).

The image recording is made by using a Polaroid camera to photograph the face of a CRT display. The

image is then reconstructed using a helium-neon laser. As presently configured, the system requires about 10 minutes to identify an object. For an antihijacking application, this is unacceptable, but work is progressing toward a real-time detection system (ref. 186).

Acousto-Optical Holographic Imager

A commercial acousto-optical imager now being marketed is based on conventional acoustical holographic techniques. This system provides previously unavailable evaluation criteria for such applications as rolled steel plate delaminations, nonbonds in aluminum honeycomb panel, high pressure diffusion bonds in lead-titanium, deteriorations of steel spot welds, fiber composite spatter-patterns, porous areas of steel castings, tubular outlines of the radial artery in the forearm, and the image of tendons in the thumb and index finger. Similar uses are possible for examining three-dimensional interiors of all types of plastic, metal, composites, or living tissues.

A typical concept model is shown in figure 61, in which the standing wave surface layer of water is used as the equivalent of an acoustic hologram. It is "read off" and reconstructed by an optical system as in conventional optical holography. This arrangement is called surface layer or liquid-surface holography (ref. 187). The degree of penetration of the object wave is governed by the acoustic impedance match between the fluid in the tank and the object's material composition as well as the absorption and scatter of sound waves within the object. Acoustic frequency tuning is therefore important in the application of these techniques, since lower frequencies will allow deeper penetration at the expense of degraded resolution and depth of field (ref. 188 and 189).

The medical application of liquid surface acoustic holography is being extensively studied at many medical centers, particularly cancer referral institutions. Roswell Park Memorial Institute and a Houston medical center are using this approach for breast cancer detection, and the University of Cincinnati is using it to map the vascular circulatory system of the neck. Queen's University employs a scanning unit for brain tumor detection, and the Battelle Northwest Laboratory has been studying a variety of applica-

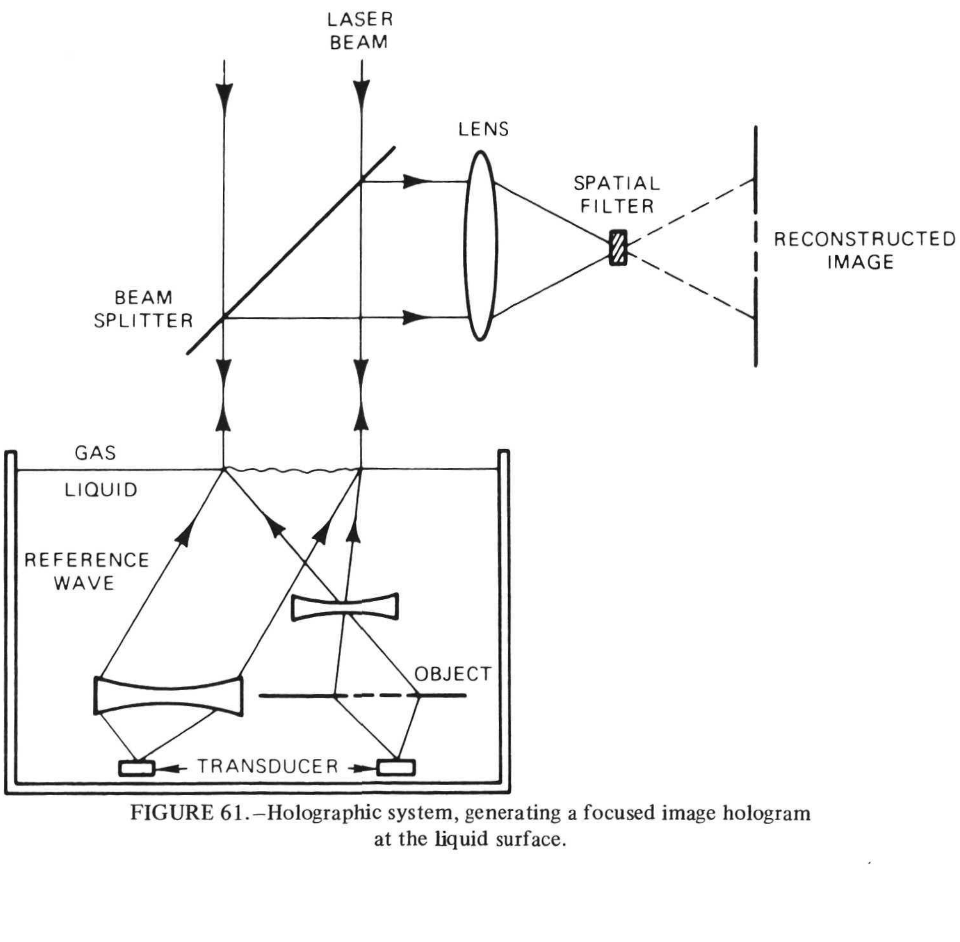


FIGURE 61.–Holographic system, generating a focused image hologram at the liquid surface.

tions, including human fetus examination to determine sex (refs. 190 through 192).

Acoustic holography provides good images not only of soft tissue but also of hard solids like metal blocks. This makes it a valuable tool in nondestructive testing or nondestructive evaluation. In evaluation, the penetrative ability of acoustic techniques permits total cross-sectional examination for flaws. For example, steel blocks as much as 19 in. thick have been completely examined (refs. 193 and 194). The major implementation to date in nondestructive teaching has been liquid-surface holography, since real-time display can best be achieved this way.

Acoustical holography does have certain current limitations. Recording is the primary problem—more so than for optical holograms because suitable recording materials do not yet exist. As a result, techniques have been developed to convert the acoustical hologram to an optical one. Another problem is loss of the three-dimensional appearance of the hologram during laser reconstruction. This has been circumvented by use of a computer technique called range-gating, in which a three-dimensional image is constructed from examination of many different range planes in the hologram (ref. 172).

Underwater Acoustic Holographic Viewing System

The U.S. Navy is sponsoring development of a real-time underwater viewing system for several uses, including their deep submergence vehicle program. Typical performance goals for such a system are ranges between 2 meters and 100 meters and a field of view of about 40 degrees with an angular resolution of about 0.4 degree. Major components of the system are an ultrasonic transmitter, an array of receiving transducers, the signal processing electronics, a TV display, and a real-time holographic image reconstructor.

The system transmits a pulse of acoustic energy from a transmitter array. At a specific time corresponding to a desired range, an acoustic receiver array is gated "on" to directly record the amplitude and phase of the signal reflected from underwater objects. Both the receiver and transmitter arrays are synchronously scanned, and the signals from each element drive a cathode ray tube displaying the resultant hologram. Real-time display of the reconstructed image is possible by the use of a holographic display tube (refs. 195 and 196).

Real-Time Holographic Display Tube

G. Goetz and others have developed a real-time display tube primarily for nonoptical holograms. The device consists of an electro-optical crystal, an off-axis scanning electron gun, and associated optics and electronics.

The scanning electron beam intensity is modulated with the information from the hologram to be displayed. Any hologram that can be transformed into an electronic raster signal can be reconstructed. The hologram is written on the crystal face in the form of an electric charge pattern, and when coherent light is passed through the crystal, this electric charge polarizes the light in varying amounts proportional to the original hologram pattern (Pochels' effect, ref. 190). This polarized light can easily be converted into an amplitude modulated pattern of coherent light by a set of crossed polarizers. This beam of coherent light amplitude modulated in perfect match to the original hologram reconstructs a virtual or real image. This device appears to have the potential of reconstructing both acoustic and microwave images, and seems competitive with pure digital computer reconstruction of these types of holograms (refs. 196, 197, and 172).

Acoustic Holographic Microscopy

The prime advantage of holographic microscopy at acoustic frequencies lies in the penetrating capability of acoustical systems. Practically speaking, it means that in biological work, differences in the mechanical properties of the specimen can be utilized to obtain high contrast imagery.

An acoustic microscope has been constructed using a laser that scans the acoustically illuminated surface. In tests to date, an individual cell of an onionskin, displayed on a TV screen, showed detail in the order of 0.001 in. Another approach in the microscopy area uses the Bragg diffraction effect for imaging. Both methods display comparable resolutions (refs. 198 and 199).

Page Intentionally Left Blank

CHAPTER 9

Holographic Data Storage, Processing and Retrieval

The eventual use of holography for extensive data storage and retrieval appears inevitable. It promises reliability, incredibly dense storage capacity, and very fast readout time. Once data has been converted into a form lending itself to holographic data storage, it is a relatively simple task to process it optically, since the same types of input and output transducers are required. Optical processing can also offer enormous increases in processing speeds because of its inherent ability to operate in parallel rather than in sequence.

Many types of operations and functions can be performed by optical processing, using complex amplitude and phase filters or inputs (hologram filters and films). Holographic films can store up to 10^6 bits of information per square millimeter, and these bits can be simultaneously manipulated in the processor in the time it takes to traverse the optical system (less than 10^{-8} sec). At least 10^{14} bits per second can be potentially processed for a 1 millimeter square input; the fastest current digital computer is six to seven orders of magnitude slower.

Modern technology, bureaucracy, and the space program are generating an ever-increasing volume of data, and conventional data storage techniques are approaching their limits. Packing densities and access times of magnetic cores, tapes, and discs are no longer adequate; 10^{10}- to 10^{12}-bit memories with access times on the order of a few nanoseconds will soon be needed. Similarly the profusion of printed material is straining the storage capabilities of libraries even with microfilm storage and retrieval systems. For all these reasons holographic storage is of increasing interest. Its best features are high-density storage and great redundancy as insurance against loss or damage of data.

Many data manipulation functions can already be performed more quickly and efficiently by optical processors utilizing holographic techniques, and these will continue to be refined. Their major potential speed advantages over digital computer processing stem from multiple channel capability. Indeed, each resolution element of the input and output plane can be considered as a separate computer channel, working with the speed of light simultaneously with all its sister resolution elements.

NASA RESEARCH AND DEVELOPMENT

NASA has been in the forefront of optical and holographic data storage and data processing investigations since 1965, through both in-house and contractor programs. Development of a high-density, compact, holographic memory for eventual space use is well under way at MSFC, while GSFC has developed designs for space-based optical data processors that use holographic filters for some operations. Some NASA efforts in this aspect of holography are:

- Techniques to aid holographic data processing
- Holographic analysis of printed circuit boards
- Holographic image deblurring and resolution enhancement
- Coherent noise elimination
- Optical read/write holographic memory system
- Optical-to-optical input transducer
- On-board spacecraft optical data processing system
- Holographic spacecraft attitude determination
- Meteor trail processing

Techniques to Aid Holographic Data Processing

Two groups at GSFC and one at MSFC have explored problems in implementing the theory of optical data processing.* A. R. Shulman and G.

*A. Shulman's NASA technical report and his more extensive textbook, *Optical Data Processing*, are particularly rich sources on the subject.

PRECEDING PAGE BLANK NOT FILMED

Grebowsky at GSFC have made valuable contributions in popularizing and interpreting holography for engineers and technicians, while J. Williams, R. Kurtz and P. Espy at MSFC are developing holographic optical processing techniques for nondestructive testing (refs. 200 through 202).

The Computer Technology Section at GSFC has experimented with the results of coherent images measured or filtered in the Fourier transform or the spatial frequency plane of an optical processor. The output can be obtained from this operation in two ways: (1) The intensity in various parts of the Fourier transform image plane can be directly measured and (2) Information can be read out after the spatially filtered image is reconstructed in the output image plane.

The first approach led to development (under contract) of a unique set of fine grain, specially shaped, wedge and ring mosaic detectors. Signals from these detectors should enable direct remote readout of amplitude and angular orientation characteristics of an input image inserted or written into the processor. This will be valuable on board an Earth resources satellite or other surveillance platform.

Figure 62 shows the signature differences generated from outputs of the angle and ring (radius) detectors. These results are for two classes of clouds: small scattered clouds at the top left, and large clouds with line structure at the top right.

To investigate the second approach, a set of electrically alterable wedge and ring filters is under development for use in the Fourier transform plane

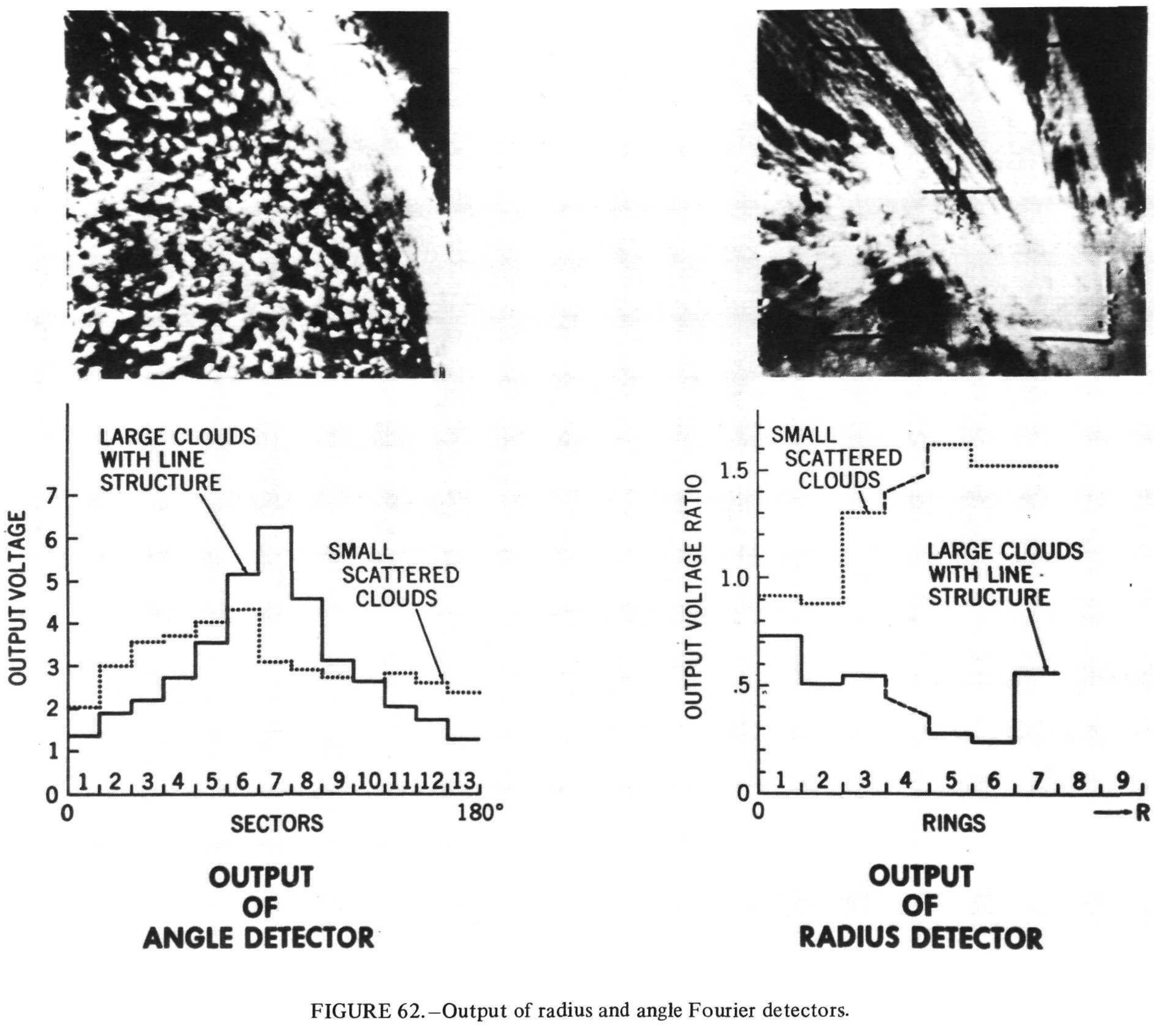


FIGURE 62.–Output of radius and angle Fourier detectors.

to block out or select specific bands of frequencies and angular orientations. Remote implementation of this approach appears more complex, since the output image must be examined in coordination with many combinations of filters. Scanning of the processed image seems to require as much information as scanning of the original. However, a system of this type might prove valuable to someone who could examine the output filtered image directly or extract enough data from a digital-only readout of the filtered output matrix image.

Plans have been made to synthesize both types of elements into a computer-controlled remote optical data processing system (fig. 63). The computer processes detector signals sensed from the Fourier transform plane and controls the filters. At the output plane, a conventional mosaic detector reconstructs the image (refs. 203 and 204).

Holographic Analysis of Printed Circuit Boards

The present Saturn Apollo vehicle was plagued by failures of its checkout control and telemetry systems caused by cracking solder joints on the printed circuit boards. NASA and contractor studies identified the prime cause of these cracking failures from the strain produced by thermal fluctuations to which the boards are subjected. Since space programs require zero defects, holography may help attain this goal.

One of the most imaginative applications of holographic data processing was the development by MSFC of a solder joint analyzer. Focused on a suspect joint, it can predict accurately the joint's expected performance if subjected to destructive testing. Essentially it is an analog optical data processor that computes the degree of similarity between the joint in its original state and the same joint after heating and cooling. This comparison is made not on the basis of image appearance but on the spatial frequencies contained in the images.

This method might be adapted to the testing of other types of electronic circuits and wiring boards in conjunction with thin film monitoring, so that layers of integrated circuits and microelectronic boards

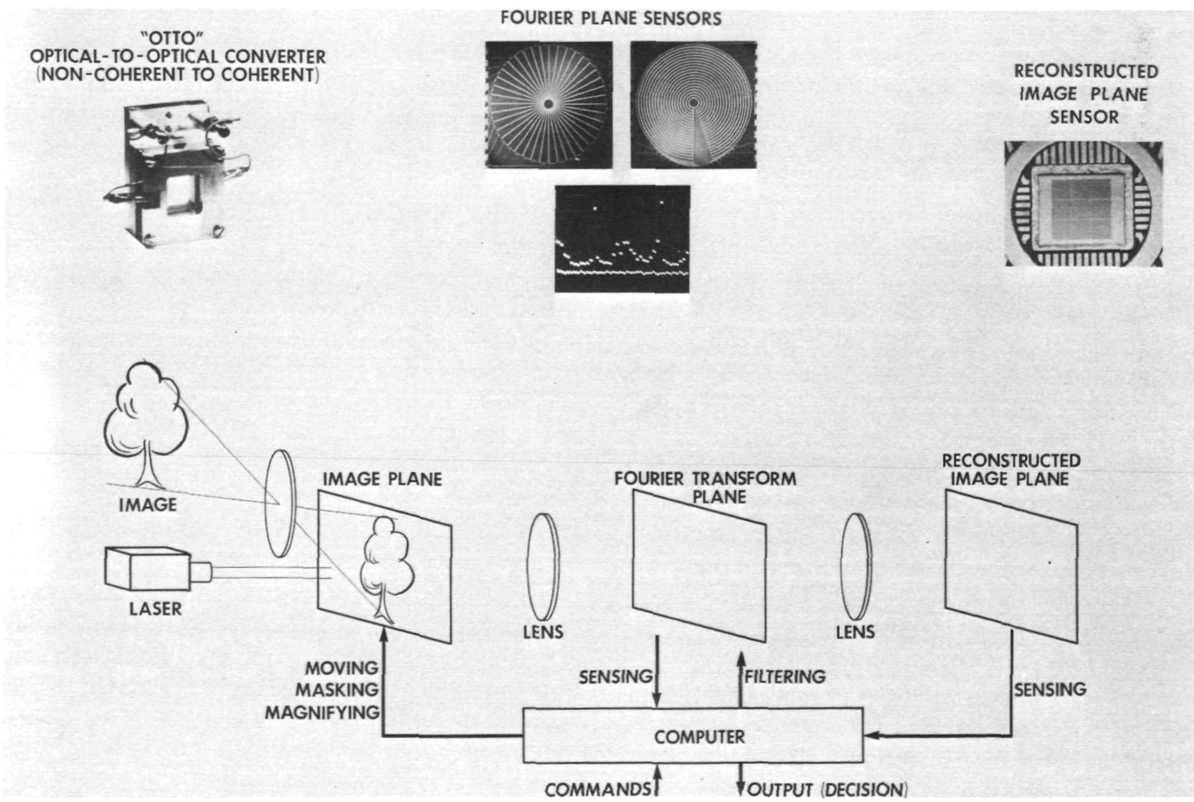


FIGURE 63.–Optical digital system with optical input.

could be inspected as they are formed rather than after completion. This could eliminate the expensive need to deposit extra layers on top of already faulty layers before testing.

This NASA-developed technique offers a method of measuring permanent deformation and fatigue elastic deformation in metals, plastics, composites, and other materials due to all types of stresses. It is also ideally suited to measuring small, nearly planar objects (refs. 205 and 206).

The correlation process can be best understood as a reconstruction of a formerly exposed hologram except that instead of reconstructing the original object wave, the reference wave is reconstructed by illuminating the hologram by the object wave (app. B). This property of a hologram illustrates the basic reciprocity between the object and reference waves that forms a hologram, a "reconstruction process" as implemented for the solder joint analyzer (app. D, refs. 200, 207 and 208).

Holographic Image Deblurring and Resolution Enhancement

NASA has supported in part Dr. G. W. Stroke's project of synthesizing and fabricating Fourier transform hologram filters. These filters were constructed to perform multiplication and division in the spatial frequency plane. Spatial frequency multiplication allows correlation and pattern recognition, while spatial frequency division permits deblurring and image restoration. Techniques were also developed to add and subtract two or more images so that extraneous information can be selectively eliminated. R. Kurtz and P. Espy of MSFC have implemented many of these operations in a laboratory environment (refs. 201, 206 and 207). Besides deblurring, these filtering techniques may be applied to Earth resources and sky laboratory experimental data processing and extraction operations. Simultaneous recognition and location of several basic pattern shapes at once in a given image are also being studied to greatly increase the speed at which pictures and images can be processed (refs. 131, 201, 209 and 210).

An x-ray photograph of the Sun was made by a large pinhole camera in a rocket (a focusing lens is impractical for this application). The holographic deblurring process sharpened the original image into a more usable one. How the deblurring works is explained in appendix D. Dr. Stroke and his staff have been refining the fabrication and utilization of these filters, but the practical problems involved in these deblurring techniques are formidable. Very subtle inhomogeneities of the film in either amplitude or phase transmission can destroy the filter operation. The filters must be extremely linear over transmission ranges of five to six orders of magnitude, and special masking techniques are necessary to produce them (refs. 207, 210 and 211).

Coherent Noise Elimination

Coherent optical processing and filtering operations are becoming quite useful despite the problem of having system noise diffraction patterns formed in the output image plane. Such patterns can be very annoying and troublesome. These "bullseye" patterns (fig. 64) are usually caused by dust or bubbles in or on the lenses. They can be reduced by carefully selecting the lens for the unavoidable minimum of bubbles and defects and keeping lens surfaces extremely clean, but neither method has proved entirely satisfactory, since perfect optical elements and a dust-free environment are not attainable.

Scientists and engineers at GSFC have devised an ingenious solution to this problem. Its efficiency can be seen in the photograph in figure 65, made at the output image plane of a single lens optical processing system: The "bullseye" difficulty has been eliminated. The fine grid of vertical lines has been placed over the transparency to illustrate dramatically that this noise removal technique will not distort any critical spatial filtering operations.

The principle behind this technique, discovered by A. R. Shulman and G. J. Grebowsky, is simple. While a photograph of the input image is being exposed, the lens is rotated about its optical axis. Figure 66 shows the physical arrangement of the equipment—basically a small motor and a commercial bell-driven rotating lens mount. Since the blemish diffraction pattern results from local imperfections and dirty spots on the transform lens, rotation of this lens also rotates the pattern. Hence, the spurious blemish images are spread out over concentric rings on the photograph. This smears out the pattern on the photograph and removes the appearance of blemishes. Detailed mechanical drawings of the motorized lens mount are available, and a patent has been applied for. Setup and adjustment of the system is critical (refs. 212 and 213).

FIGURE 64.–Coherent output image with noise diffraction patterns.

FIGURE 65.–Coherent output of gridded range.

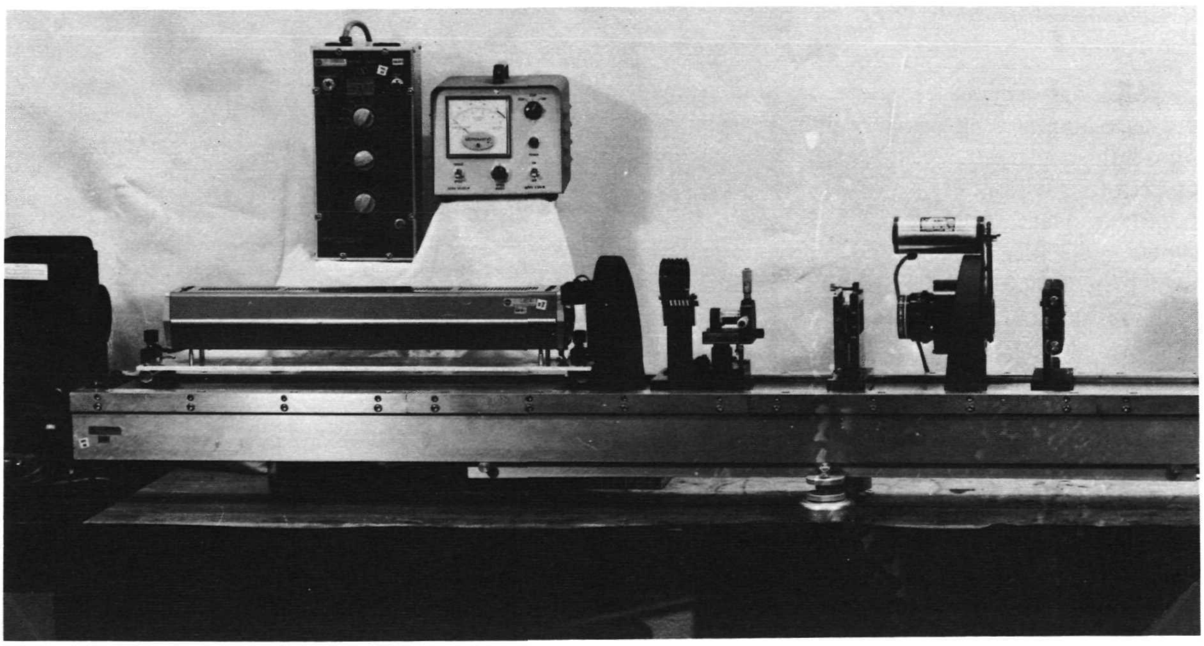


FIGURE 66.–Experimental setup of coherent noise removal.

Optical Read/Write Holographic Memory System

NASA has pioneered research in holographic mass memory devices because of their adaptation to compact, large-capacity computers in space vehicles and satellites. NASA has also been vigorously pursuing development of spaceborne optical data processing equipment in hopes of reducing for transmission the vast quantity of raw data gathered by high resolution sensors and presently relayed from satellites or other remote platforms.

The feasibility of a 10^{10}-bit optical memory was

investigated by Carson Laboratories, Inc., under contract to ERC. Using available technology, this system could be built using either a surface or a volume hologram (ref. 214). Memory size up to 10^{12} bits is planned in a design concept by Radiation, Inc., for MSFC (fig. 67). A subarray is recorded on one small part of the overall hologram; the entire hologram array is made up of repeated different subarrays recorded adjacent to each other. If the recording medium is conventional film, the exposed hologram is then processed and can subsequently be reconstructed, a subarray at a time, by the reference beam.

Readout and recording devices in this system are of critical importance. The reference beam must be accurately aimed at the particular area of the hologram to be recorded, and the positioning for readout must be exact; these two operations determine the access time and error rate (respectively) of the process. Conversion of each subarray to computer usable data can be achieved using an array of

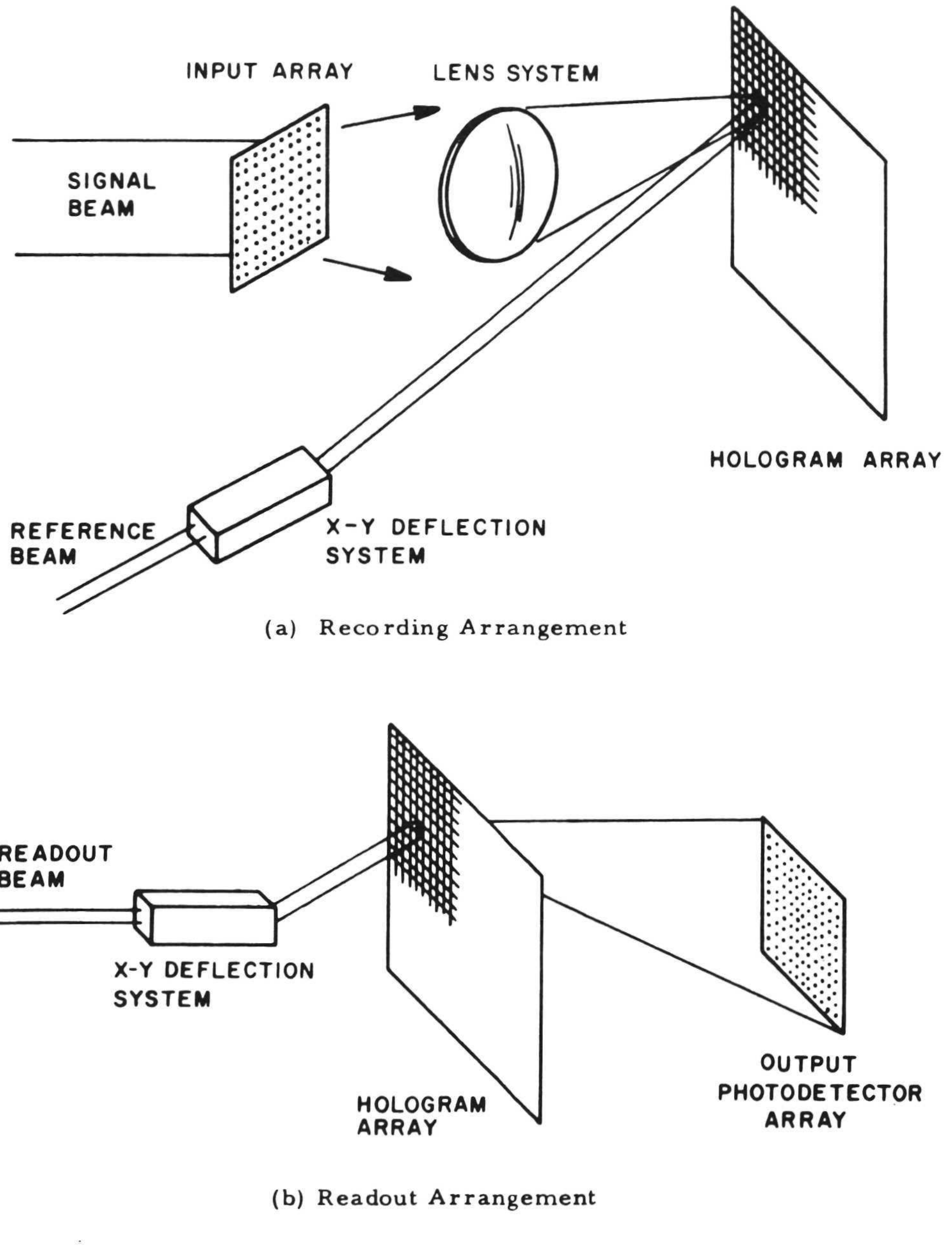


FIGURE 67.–Holographic memory.

photodetectors that duplicate spacing between the dots in the image. Thus the entire array can be transferred in parallel fashion to the computer (refs. 215 through 217). An advanced implementation of this concept has now been fabricated (fig. 68).

The insertion of data to be recorded requires careful design, especially if high-speed operation is required. Radiation, Inc., has also designed a block data composer that uses electrically alterable apertures (fig. 69). The data can be presented in either serial or binary form. Currently the major problem with this device is in the read/write portion of the memory. The composer can be recycled about 10^6 times before it needs to be replaced, while the erasable photoplastic hologram recording material has a lifetime of about 100 recycles (ref. 218).

One of the major considerations in developing any type of holographic memory is the recording material. The desired features are:

High resolution
Fast recording
Minimum processing
High stability
High reversibility
Easy erasure and/or overwrite
Broad spectral response
High angular sensitivity
High uniformity

Resolution governs the packing density and in turn the physical size of the memory. Recording speed and processing requirements determine storage rate. Stability is needed for any extended data storage; this encompasses not only dimensional factors but also sensitivity to light exposure and environmental conditions. Reversibility governs the number of times the material may be recycled. The capability of selective erasure and overwrite governs applicability to read/write memories (as opposed to read-only memories). In some cases, only destructive readout may be feasible, thus requiring a rewrite cycle after readout. The spectral response should be sufficiently wide to allow the use of various frequency laser units for possible spectral multiplexing. A high angular sensitivity enables the storage of multiple subarrays over the same location. Finally, high uniformity of the material's sensitivity is required for reliability and low error rates.

Many materials have been studied for holographic recording. Photographic emulsions can obviously be used only for read-only memories, although the new

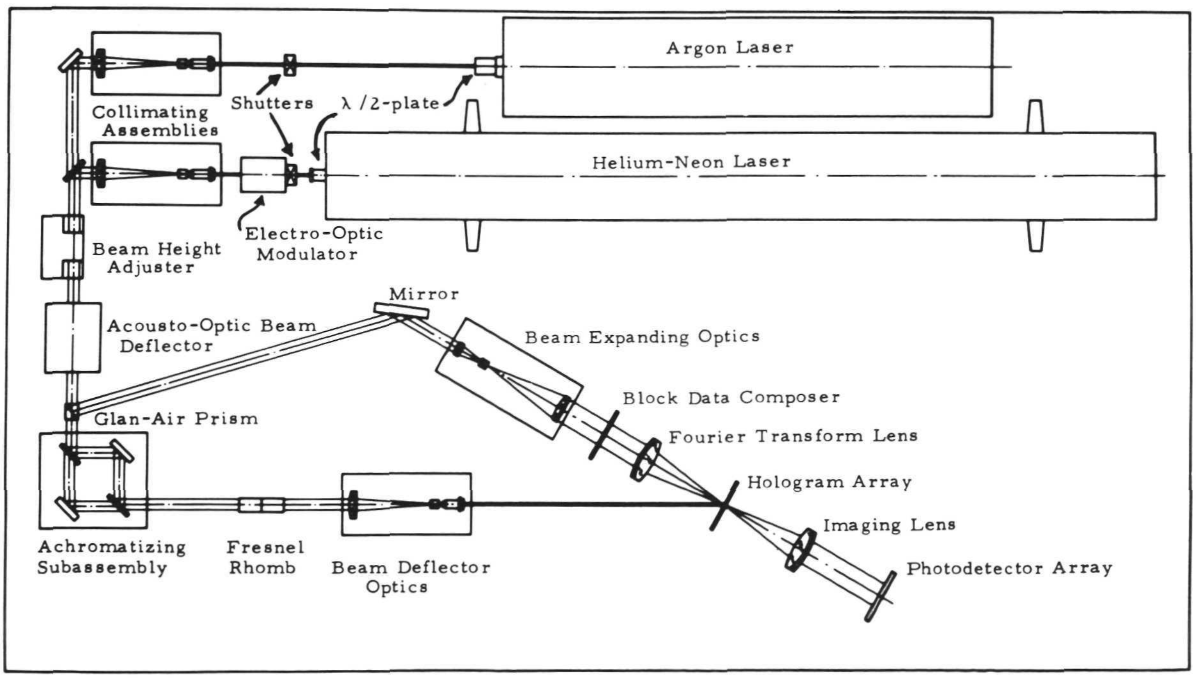


FIGURE 68.–Optical read/write holographic memory system layout.

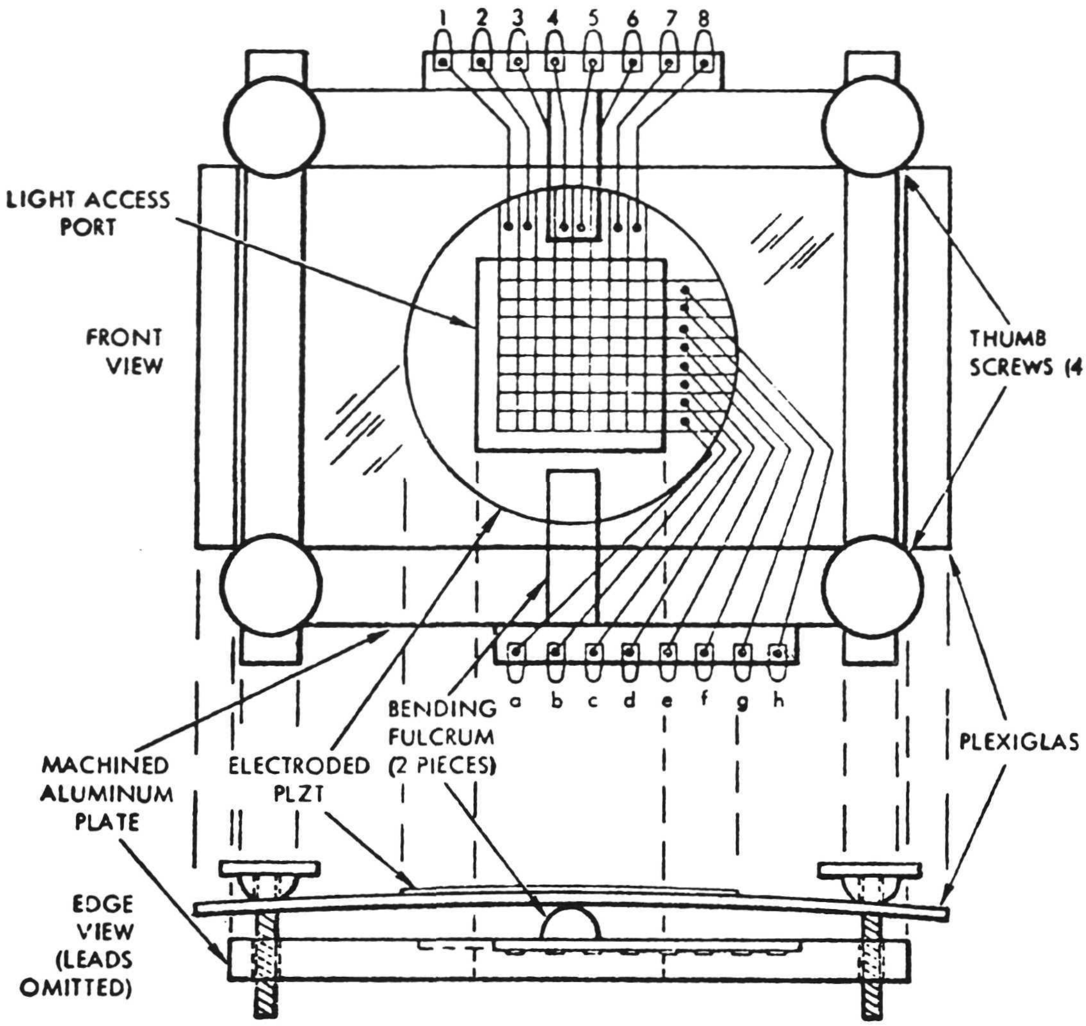


FIGURE 69.–Front and edge views of the electrically alterable block data composer.

arsenic trisulfide can be erased. For uses that require frequent recall of extensive tabulated data, this may offer the best system. An MSFC study by Radiation, Inc., recommended using photo-plastics or manganese bismuth for read/write implementation (refs. 216 through 218).

Some alternate materials under investigation are lithium niobate crystals for storage of up to 1000 holograms per crystal (BTL); alkali-halide crystals for 10^{18} bit storage (Carson Laboratories); strontium-barium niobate crystals (Sperry Rand); iron-doped lithium niobate crystals (RCA); and arsenic trisulfide and other inorganic photochromic materials (RCA) (refs. 219 through 225).

North American Rockwell, IBM, BTL, and New York's Off-Track Betting agency are also investigating holographic mass memories (refs. 226 through 228).

Optical-to-Optical Input Transducer

A very important contribution to this area is GSFC's development of the optical-to-optical converter (OTTO) input device (fig. 63). This converter can produce a coherent image from the input of a relayed incoherent image. The importance of this development is its potentially wide range of application. Not only will it be valuable for data processing operations, but it fills the need for a near real-time input composer in present holographic optical data storage and holographic computer memory systems.

OTTO operates by using an auxiliary front end optical system to pick up a remote object and image it into the OTTO converter surface. Figure 70 shows the design and functioning of an optical relay that could be used. The coherent laser beam illuminates the OTTO surface and transmits a negative of the incoherent image, irradiating it through to the processor.

The OTTO device is not ready to be incorporated into a spaceborne system, but an experimental optical data processing system has been demonstrated at GSFC with the OTTO as its input device. OTTO's major limitation at present is the lifetime of its sensitive layer (currently 100 hours of continuous service) and its response time (approximately 1/10 sec). Resolution capability is quite good at about 40 line pairs/mm. Perfection of the device for long term unattended use with extremely rapid frame rates may be 5 to 10 years away, but limited use in certain applications such as holographic computer memories or data storage that provide easy access and replacement may be only a few years away.

Two versions of the OTTO are being developed. One uses a single layer of bismuth silicon dioxide. The other is the previously mentioned OTTO which consists of a sandwich-constructed matrix of two layers (one a cadmium sulfide photoconductor and the other a liquid crystal layer) between two transparent conductive plates (ref. 229).

On-Board Spacecraft Optical Data Processing System

NASA investigation of an on-board optical processor concept started with theoretical work done by Oakland University and North Carolina State University for ERC. Basic equations were derived to show that a single-element lens or mirror could be designed

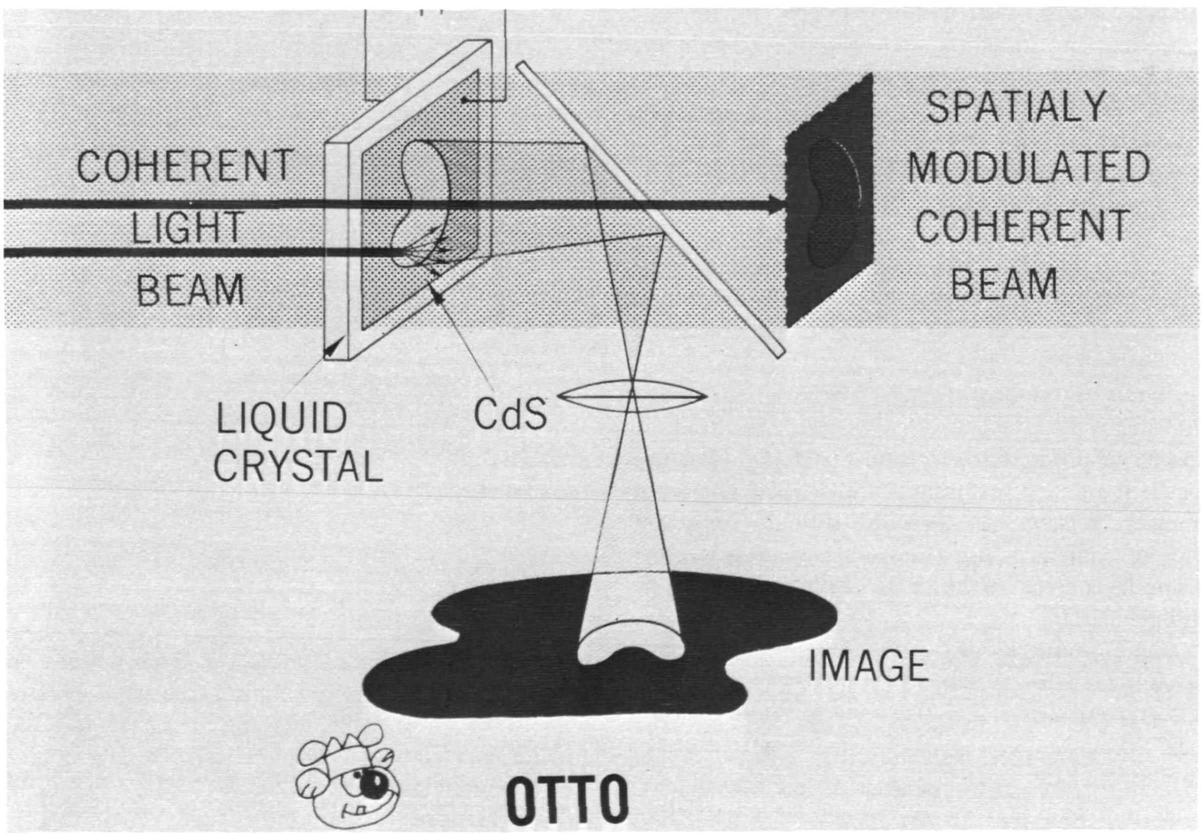


FIGURE 70.–OTTO light transducer.

as a processor to include the essential input signal, transform filter, and output image planes (refs. 230 and 231).

A. S. Husain-Abidi and T. K. Krile of GSFC experimentally demonstrated the Fourier transform capabilities of parabolical mirror segments by recording transforms of variously shaped objects. They also pointed out that the use of these elements rather than lenses for data processing resulted in freedom from spherical and chromatic aberrations, eliminated front surface reflections, and considerably minimized astigmatic and comatic distortions. Such a processor could be constructed without the need for perfectly homogeneous and isotropic optical elements (a usual requirement for lens systems) and with a more compact design, due to the folding of the optical path. It could also be used with ultraviolet, infrared, or even x-ray electromagnetic radiation, which is difficult, expensive, or impossible with lenses (ref. 232).

The unique three-mirror segment folded processor shown in figure 71 was designed with on-board satellite data processing in mind. The Optical Data Processing and Inflight Computer (OPDIC) is at the bottom of the figure. Its folded optical path schematic is diagrammed in the middle, as compared to the normal straight line optical path at the top. The size of the folded optical computer is 6 by 3-1/2 by 1-1/2 in. The source of coherent light is a tiny gallium arsenide injection laser (1). Fourier transform ring and wedge filters or detectors can be inserted in the Fourier transform plane (7), while the output is imaged on the reconstruction plane (9) and the input is placed in plane (5).

Simple filtering operations have been performed with this system, such as a blocking experiment in the Fourier or frequency spectrum plane (fig. 72). The spatial frequency spectrum of the vertical line input (a) was blocked off, then the output image was photographed as in (c). The spectrum consists of the points in a horizontal line in the transform plane, displayed in (b) (app. D).

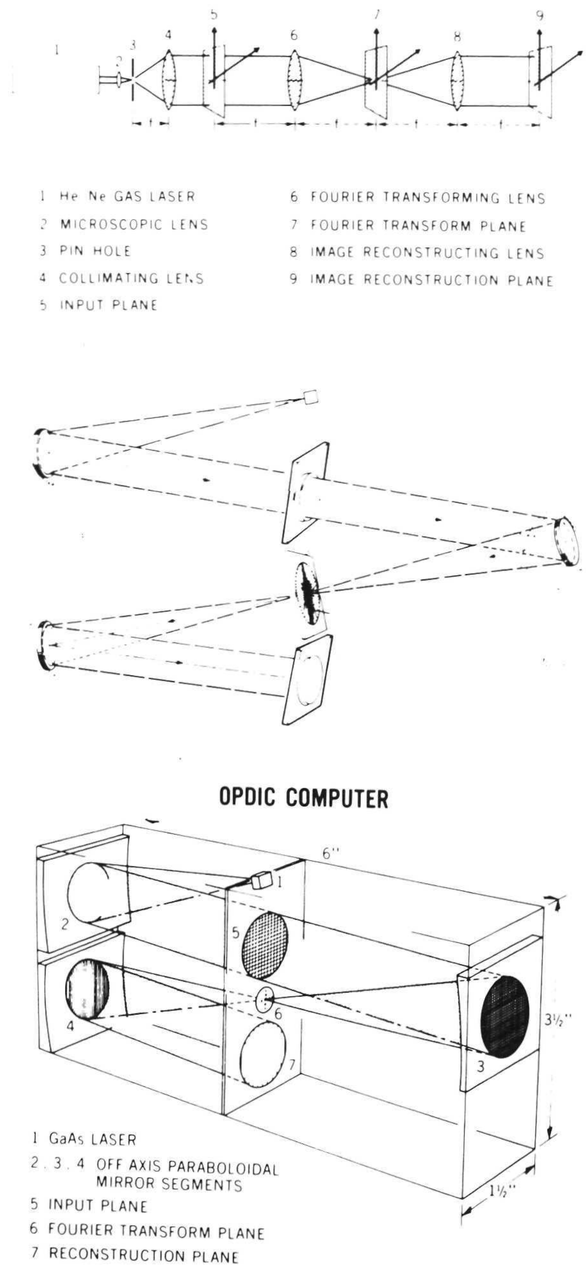


FIGURE 71.–OPDIC computer.

The system was also used in optical correlation experiments. When a brain tissue microscope slide (fig. 73) was placed in the input plane and correlated with a holographic matched filter (placed in the transform plane) of the same slide, the bright, sharp, autocorrelation spot to the right of the figure was obtained as output. Hopefully such an operation conducted on a future satellite could locate and automatically continue to track a given pattern or landmark of the viewed sensor imagery. Precise readout of these same imagery areas will be performed and compared automatically with the previous readout overpass to detect changes in their spectral or intensity distributions (refs. 229 and 233).

A computer-aided folded optical correlator system is under development at GSFC. A correlation spot

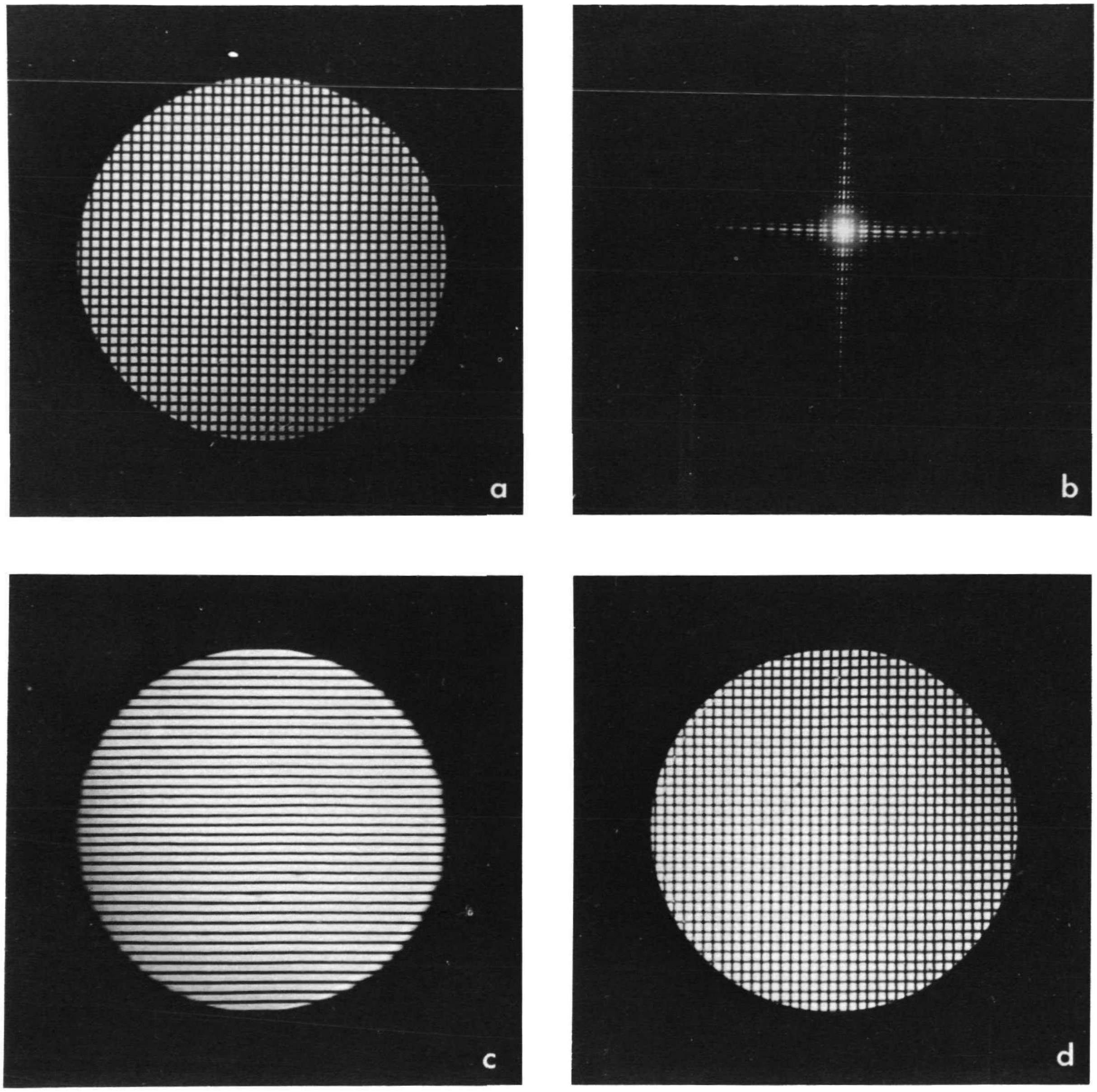


FIGURE 72.–Spatial filtering experiment. (a) a wire grid in a circular aperture (the object transparency), (b) Fourier transform of (a), (c) the filtered reconstructed image, (d) the unfiltered reconstructed image.

monitored by an image dissector tube and the output of this tube is interfaced with an IBM 1800 computer to control the physical position of the input information. The OTTO input matrix composer may eventually be used to insert data into this optical processor, but such a completely remote automatic system may be as much as 10 years away (ref. 229). Long before that, however, modifications of the system may make it possible to perform terrestrial data processing tasks which, although less demanding, may be even more important. Some exciting possibilities are automatic tracking and correlation of features contained in sets of organic and biological photomicroscope slides made by optical, x-ray, or electron microscopy instruments: for example, slides of brain tissue, optic nerves, nerve cells, blood tissue, vital organs, bacteria, minerals, crystals, and metal structure and flaws.

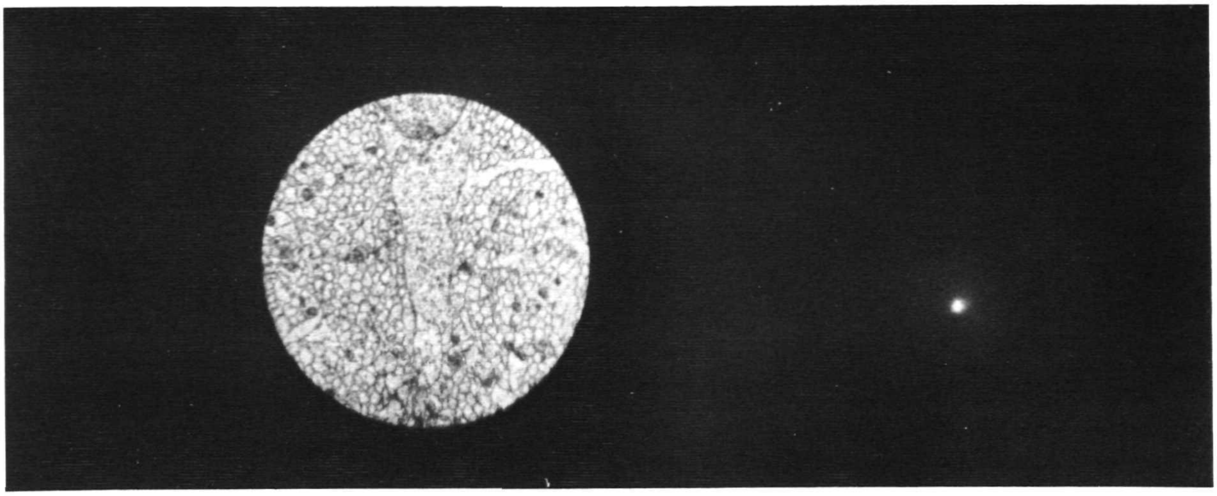


FIGURE 73.–Holographic correlation of brain tissue slide.

Holographic Spacecraft Attitude Determination

Another potential use for holographic data processing and storage is attitude and position determination by star map correlation. ERC supported a study of some of the prime components of this concept. The basic theory is to match the star position output of a star tracker or scanner with reference star position holograms in a matched filter correlator. Recognition of a correlation spot indicates lock-on of the observed star field with the reference star field, while the position of the correlation spot indicates the exact bearing from the optical axis of the previously stored reference star field. The angular coordinates of this displacement can be used to calculate the attitude of the optical axis and of the satellite or space vehicle, thus eliminating the need for a restricted knowledge of star positions with respect to space vehicle axes or for a special vehicle maneuver now required with star mapping guidance systems. GE has been exploring practical materials and techniques for storing a large number of star field patterns (refs. 234 and 235).

MSFC has been supporting development of data processing techniques for detection of meteor trails; this research resulted in selectivity and noise rejection specifications for suitably matched filters (ref. 236). North Carolina State University and the University of Michigan conducted for NASA a series of theoretical studies of optical data processing. North Carolina State University derived the spectrum errors in the Fourier transform plane caused by geometric deviations of the input plane (ref. 231). The University of Michigan concentrated on methods for preparing high diffraction efficiency hologram materials. There a variety of bleaching techniques were developed using two- and three-dimensional gratings, and experiments were performed with techniques for multiplexing holographic black and white and color images on regular and photochromic materials (ref. 237). J. N. Hallock of ERC applied for a patent covering the sensitizing of hologram materials by a preexposure technique; this procedure permits relatively insensitive real-time holographic storage materials to be used for some applications (refs. 238 and 239).

COMMERCIAL ENDEAVORS

Several interesting advances have been made in industrial holographic data storage and processing.

Commercial Holographic Personnel Identifications and Verifier Systems

To date holographic identification systems, personnel verifiers, and the conventional optical processor have achieved full commercial status. The potential market for these devices looks promising, but so far they have attracted only a few users with specialized requirements. It takes a great deal of technical expertise and capital to become seriously involved in producing these devices.

At least two commercial versions of a holographically recorded identification card and personnel

verifier are currently on the market. Both have a large number of uses, such as verifying credit cards, passports, and bank passbooks and checks. Controlled access and entrance to military installations, research laboratories, vital computer areas, records depositories, public buildings, bonded warehouses, communication control centers, drug supply areas, currency and valuables handling areas, and cargo truck handling can be simplified by using these systems.

With one system, a hologram of the fingerprint and signature of the bearer is recorded on a standard plastic identification card. To gain access to an automatically guarded area, a person inserts his fingertip into the built-in verifier. Using optical matched filtering, the verifier compares the live fingerprint with the recorded one to determine validity; the process takes 3 to 5 sec using a 90-lb compact unit with 120 W power (ref. 240).

Another system not only records the required identification information as a hologram, but then scrambles it by an optically random code. When the identification card is presented to the reader terminal for decoding, the same random optical code in the reader allows the information to be unscrambled and holographically reconstructed via a closed TV monitor output. The great advantage here is that if the coded information falls into unauthorized hands, it cannot be decoded even by sophisticated optical equipment without the random code. When connected to a local memory bank by computer, it can also control access like the first system (ref. 241).

Hybrid Holographic/Digital Computer Optical Processor

The Electro-Optics Center of Harris Intertype has developed a flexible hybrid holographic/computer optical data processor, the closest an advanced system has been brought to production. The photograph of this unit (fig. 74) shows the optical bench and lenses, computer, and readout equipment. The device, called the Hybrid Optical Processor, has been used to determine the vector velocities of cloud patterns taken from ATS-III satellite imagery. This operation requires the complex cross- and auto-correlation functions to be calculated, located, and plotted on a series of sequenced cloud imagery. Because conventional film processing delays are intolerable, complex filters must be used that are generated in situ on photoplastic materials. This process has also been used for pattern recognition, character recognition, spectral analysis, and image quality assessment.

The major improvements in the hybrid processor over conventional commercial optical data processors are its selective output characteristics and in-place generation of photo-plastic complex filters. Use of a PDP-8/I digital computer in the processor permits output to be coupled either to a cathode ray tube display or to hard-copy output. The computer readout devices and associated threshold circuits have been designed to reduce substantially the amount of output data displayed compared to the total amount of data processed (ref. 242 through 244). The major limitation of the Hybrid Optical Processor is the lack of an input device to rapidly convert electrical and incoherent optical signals into a suitable coherent optical image. The OTTO device under development by GSFC may help alleviate this problem (ref. 229).

Microhologram Recording/Retrieval Systems

Radiation, Inc., and Sperry Rand have developed a few high density data storage systems to record and retrieve two-dimensional microholograms. Another Radiation, Inc., system developed for the Department of Defense can automatically or manually read out one-dimensional coding information recorded on unused portions of standard microfiche or microfilm frames. However, the cost of these devices presently limits them to users who either handle a large volume of dissemination copies or must use extremely high density storage in combination with high quality retrieval imagery. Holographic recording of high density information such as that contained in pictures, microfiche, or microfilm involves some of the same basic concepts needed for the development of holographic computer memories (refs. 245 and 246).

The Radiation, Inc., microholograms will be able to store up to 200 times as much information as a microfiche in a standard 4 by 6 in. card. Its emulsion surface stands up much better to rough treatment, and duplication from a master microhologram is cheaper and easier. Development of these systems was enhanced by the company's experience in developing an extremely high density holographic memory for MSFC (ref. 237).

D. H. McMahon of Sperry Rand has been investigating a slightly different approach to producing holographic recordings, either from standard microfiche or directly from the original material. He has

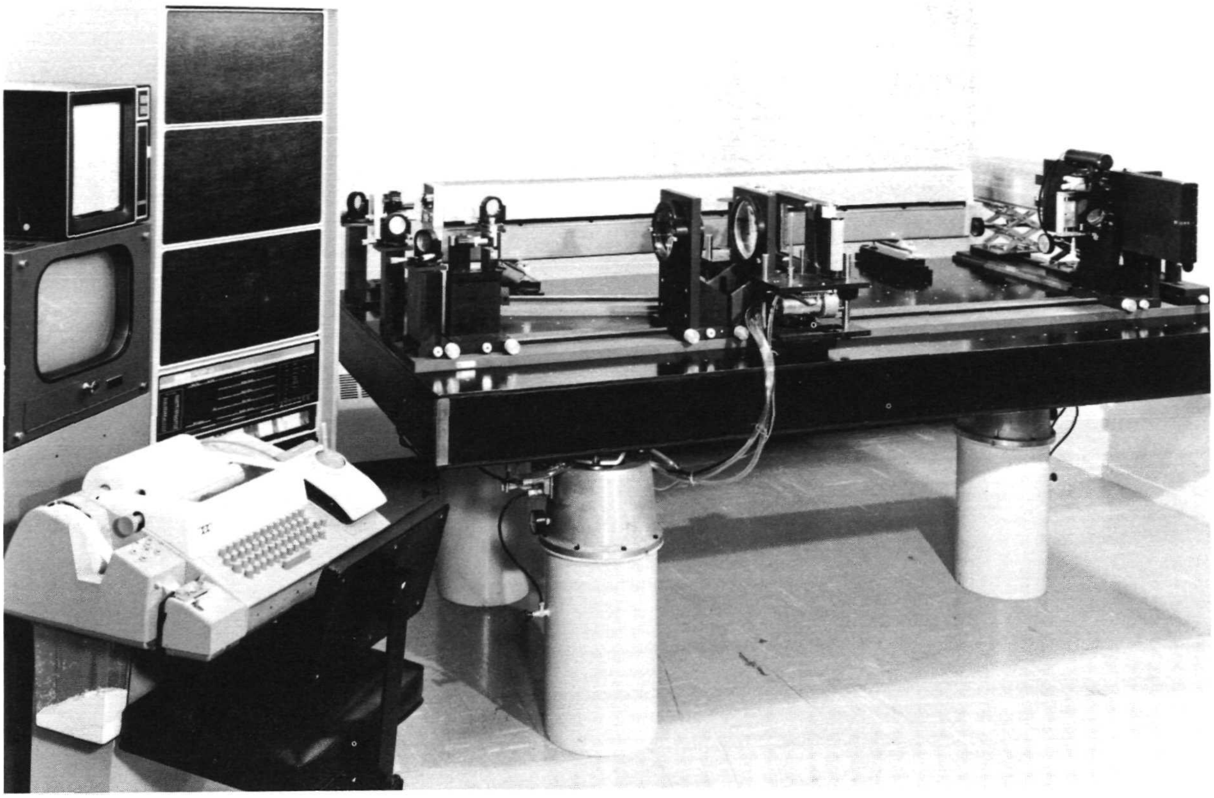


FIGURE 74.–Hybrid holographic/computer optical data processor.

succeeded in recording microholograms using Fourier transform holography techniques at an equivalent density of about 600 pages per fiche–about 10 times the normal microfiche density and about 1/6 the density now possible with ultrafiche techniques. He believes that holographic recording of this type will ultimately be cheaper, easier, more flexible, and easier to read out (ref. 245).

Both Radiation, Inc., and Sperry Rand groups have also built experimental viewers that have largely eliminated the effects of laser speckle. This is done either by mechanically oscillating the screen or by using a "dynamic screen" viewer that also increases the contrast of the projected reconstructed image.

Holographic Spectral Analysis

Holography has been cleverly used to perform spectral analysis of a single pulse from a laser. A basic property of the hologram is extremely narrow wavelength selection, because stationary interference patterns are not produced unless the object and reference waves are of exactly the same frequency. Making use of this fundamental concept, C. C. Aleksoff of University of Michigan developed a technique to disperse the multiple frequency modal patterns of a pulse laser into a series of concentric rings. Interference of this pattern with diffused projection of the axial and transverse mode patterns of the same laser (object beam) allowed reconstruction of the instantaneous modal pattern of a given frequency at the time of exposure. This technique might be modified to record other simultaneous multiple frequency events (ref. 248).

Velocimeter Holographic Analysis

For the U.S. Air Force, the Tennessee University Space Institute has been investigating optical processors to automatically reduce the inline holograms

made of particle flow fields. Depth positions of known-diameter particles in a direction parallel with the optical axis are determined by matching the hologram reconstructions with a series of optical holographic matched filters. Each filter corresponds to a given depth, and the series spans the total depth range of the recorded hologram. Although the cost appears comparable with alternative semiautomatic readout techniques, the matched filter technique may give better accuracy of the depth position of particles (ref. 249).

Holographic Electrical Signal Processing

M. King has demonstrated that real-time holographic recording of wideband electrical signals up to 3-MHz bandwidth is feasible using the optical output of acousto-optical ultrasonic light modulators as the basic object wave. The technique could be adapted to record bandwidth signals up to 100 MHz if the most advanced argon-pulsed laser and acousto-optical modulator were used. Some degradation of the reconstructed wave forms was observed, however (ref. 250).

Synthetic Large Optical Aperture Holograms

J. Wilezynski of IBM has invented a means of generating over 200-in. diameter synthetic aperture optical images by an innovative holographic process. The heart of the discovery is the processing of actual images from several smaller optical apertures into a form equivalent to the resolution of a larger optical aperture (ref. 251).

Holographic Fingerprint Identification

The University of Michigan and others are perfecting methods of instant fingerprint identification. The greatest problem is adjusting the extreme sensitivity of the process so that a given class of fingerprints, as well as only one individual set, can indicate partial matches (ref. 252).

Infrared Holograms

Several researchers have made successful holograms with infrared energy. F. M. Shofmer of Environmental Systems Company used conventional Kodak IR Film 2481 to make inline holograms (ref. 253). LTV used a thermochromic crystalline type material, and the Japanese are experimenting with photochromic films and liquid crystal area detectors to record infrared holograms at the 10.6 μm wavelength. Before reconstruction can take place, the thermo-image on the detector must be recorded on ordinary film (refs. 254 through 256).

The Army described a technique for analyzing and recording holographic information on an image dissector. By this method, holograms were electrically transmitted and remotely reconstructed, allowing data display at many remote locations. Storage of images at a central master file and remote retrieval and reconstruction may also become feasible (ref. 257).

Other Improvements

J. W. Goodman and J. D. Gaskill have conducted experiments for the Air Force on methods of improving the image quality obtained by remote holography over long paths through the atmosphere. The concept permits an undistorted object to be reconstructed even though nonhomogeneous elements are varying with time, based on the fact that the perturbed image of the object and point source can be recorded while simultaneously traversing through the same part of the distorting medium. Further study of these processes may enable hologram signal-to-noise ratios to be enhanced in the future; this development could have far-reaching results in certain interferometry, data processing, and recording applications (refs. 258 and 259).

W. D. Hall of the University of Michigan is developing a thermoplastic holographic recorder that will use an electron beam read-in of the stored electric signal. Current research is concentrating on the coherent laser beam read-out of the stored images and effects caused by random thickness variations of the thermo-plastics (ref. 260).

534-778 O-74—7

Page Intentionally Left Blank

CHAPTER 10

How to Get Started in Holography

IN-HOUSE CAPABILITY VERSUS OUTSIDE SERVICES

A company can begin using holography to solve its engineering, inspection, and quality control problems either by establishing in-house capability or by engaging the services of an outside holographic applications service laboratory (ref. 261).

Complete holographic systems and associated optical components can be leased, or traveling holographic laboratories and their trained staffs will establish temporary residence at the client's facilities (ref. 262). One company conducts a training class for purchasers or lessees of its holographic laboratory system for about $200, covering a 3-day formal and applied course for four people. Its leasing fee is about 10 percent of the total purchase price of the equipment per month. The holographic laboratory systems range in price from $1540 to about $24 000, and include lasers ranging from a 1 mW continuous wave helium-neon laser to a 500 mW argon laser (ref. 263). Another company has designed a special small holographic laboratory system and claims that it "comes partially preassembled and may be set up within a few minutes–approximately 2 hours' time is estimated for reading the instructions, exposing, developing and viewing the initial holograms" (ref. 264).

For straight industrial production and inspection applications, several companies sell, lease, or rent pulsed laser holographic systems that can make various types of holographic interferograms. One company fully equips its service laboratory with cw and pulsed ruby holographic laser systems and associated equipment and staffs it with electronic and mechanical engineering holography specialists (ref. 261). (The pulsed laser systems are more expensive than cw lasers, but usually do not require such an elaborate vibration-isolated optical bench or table.)

Lists of companies selling, leasing, and renting holographic systems, services, or equipment can be obtained from the latest *Laser Focus Buyers Guide* (January issue), the *Electro-Optical Master Catalog* and the *Electro-Optical Systems Design* trade magazine (July issue) under such headings as Services Systems, Holography, and Nondestructive Testing (refs. 265 and 266).

Persons with experience and training in optical theory and laser systems are probably best qualified to perform holographic analysis and testing, although some electrical and mechanical engineers have completed university and industrial courses in the fundamentals of holography. The ideal holographic team is an optical engineer or scientist and a mechanical and/or an electrical engineer. The optical specialist should know some practical photography and laser technology, since film is the usual medium for recording laser beam holograms. If acoustic or microwave holography is to be pursued, then an acoustic engineer, electrical engineer, or physical scientist is highly desirable. The field of holographic data storage, processing, and retrieval is even more demanding and is recommended only for an expert. A solid state physicist or engineer with a sound background in optical theory and experimentation would also be a valuable addition to a team.

Further sources of information on holographic theory and practice are thorough and readily available (see references and bibliography). For the mathematically inclined, Collier, Burckhardt, and Lin's *Optical Holography* is a comprehensive textbook. For those with less mathematical background, an excellent presentation of basic engineering considerations may be found in *The Engineering Uses of Holography*, edited by E. R. Robertson and J. M. Harvey. Shulman explains very lucidly in *Optical Data Processing* most of the fundamental optical principles and derives at least the first order holographic equations from the viewpoint and back-

ground of the electrical engineer or technician. Caulfield and Lu clearly describe the basic uses of holography in their book *The Applications of Holography*, using only the mathematics necessary to quantitatively illustrate central principles.

Other sources of basic background are the many excellent review articles that have appeared on holography in technical journals, trade magazines, and general magazines. Some of these follow:

Four Holographic Invited Papers. Proc. Institute of Electrical and Electronics Engineers, Inc. (IEEE), Sept. 1971.

Kock, W. E.: Fundamentals of Holography. Laser Focus, Feb. 1969, pp. 26-34.

Gabor, D.; Kock, W. E.; and Stroke, G. W.: Holography. Science, vol. 173, no. 3991, July 2, 1971, pp. 11-23.

Gabor, D.: Holography, 1948-1971. Science, vol. 177, no. 4046, July 28, 1972, pp. 299-313.

Proc. Engineering Applications of Holography ARPA Symposium, Feb. 16-17, 1972, Los Angeles.

Holography. Seminar Proc. Society of Photo-Optical Instrumentation Engineers (SPIE), vol. 15, 1968.

Developments in Holography. Seminar Proc. SPIE, vol. 25, 1971.

Williams, J. R.; and Jenkins, R. W.: Non-Destructive Testing by Holographic Interferometry. Physik in unserer Zeit, in press.

Lessing, L.: Getting the Whole Picture from Holography. Fortune, Sept. 1971, pp. 110-118.

The most comprehensive review to date is contained within the four invited papers in the September 1971 *Proceedings IEEE* issue: It includes over 50 pages on optical, microwave, acoustic, and digital holography, and is written for those with sophisticated electrical and radar engineering and mathematical backgrounds. Many references are provided for a thorough literature search in the field.

The optical and electro-optical trade magazines are probably the best way to keep up with advances and new applications in holography:

Lasersphere, published semimonthly by Sphere, Inc., R. R. 3, Box 290, Michigan City, Ind. 46360.

Laser Focus, published monthly by Advanced Technology Publications, Inc., 246 Walnut St., Newtonville, Mass. 02160.

Optical Spectra, published monthly by Optical Publishing Company, Inc., Lenox Rd., Pittsfield, Mass. 01201.

The Laser Weekly, published by Lawry-Cocraft Abstracts, 905 Elmwood St., Evanston, Ill. 60202.

Electro-Optical Systems Design, published monthly by Milton S. Kiver Publications, Inc., 222 West Adams St., Chicago, Ill. 60606.

Microwaves/Laser Technology, published monthly by Hayden Publishing Company, Inc., 50 Essex St., Rochelle Park, N.J. 07662.

Some of the leading holography companies will send data on new applications in a periodic newsletter (ref. 256).

Optical publications are also a good source of holographic information:

Applied Optics, published monthly by Optical Society of America, 335 E. 45th St., N.Y., N.Y. 10017.

Applied Physics Letters, published semimonthly by American Institute of Physics, 335 E. 45th St., N.Y., N.Y. 10017.

Journal of Society of Photo-Optical Instrumentation Engineers (SPIE), published bimonthly by Publications Committee of the Society, 118 Palos Verdes Blvd., Redondo Beach, Calif. 90277.

Journal of the Optical Society of America (JOSA), published monthly by American Institute of Physics, 335 E. 45th St., N.Y., N.Y. 10017.

Proceedings of the Institute of Electrical and Electronics Engineers, Inc. (IEEE), published monthly by IEEE, 345 E. 47th St., N.Y., N.Y. 10017.

Various NASA facilities are willing to assist qualified organizations in developing holographic capability. NASA is particularly interested in demonstrating practical industrial applications developed through aerospace research and now adaptable to commercial purposes. NASA's Technology Utilization Division has branch offices at each major NASA center, and can provide any interested person with the latest holographic materials published by NASA. This division also can arrange for qualified individuals to meet the NASA specialists most closely associated with their particular area of interest. Small funding grants are occasionally available to a company demonstrating an ability to adapt aerospace applications to its own needs.

Before a discovered or developed application can be commercially marketed, the soliciting company should perform a careful patent search for associated or conflicting prior patents. The Holotron Corporation, a small holding company owned jointly by E. I. Du Pont de Nemours and Company and Scientific Advances (itself a wholly owned subsidiary of Battelle Memorial Institute), holds a majority of basic patent rights on holographic technology, including basic patents on the off-axis sideband holography technique and on the current technique used for acoustic holography. Some dispute the claim on the latter two, and one expert insists that the "off-axis" holographic technique is in the public domain, but no court actions have yet developed. Although three companies (GCO, Inc., Holosonics, and Joseph Strick of New York) have quietly entered into licensing arrangements with Holotron, at least two companies

(RCA and Holograf, Inc.) do not believe that they need a license to market their holographic products (refs. 267 and 268).

Several holographic patents and patent disclosures have been assigned to NASA centers and NASA contractors; rights to use these patents can usually be obtained from NASA by qualified companies demonstrating a useful and salable product. The Technology Utilization Office or Patent Office at the appropriate NASA Center can help interested companies with this type of problem.

HOLOGRAPHIC STATE-OF-THE-ART REVIEW

Table 3 summarizes the current state-of-the-art in holography by functional discipline and R&D status. The terminology used in the Specific Use or Product column does not in most cases coincide with official project names or trade designations. Work by NASA centers or NASA-funded contractors is italicized in the table.

Table 3 clearly shows the diversity of holography and the advanced status of many of its branches—especially the first five categories. Commercial off-the-shelf equipment is also available for microwave and acoustic-ultrasonic holography. On the other hand, although some optical data processing equipment is commercially available for identification and personnel verification, no holographic data storage or retrieval equipment is at present being marketed. The disciplines of seismic holography, holographic optics, and computer- generated holography are in a research status and progressing slowly. Overall, the greatest concentration of current projects is in the category of holographic interferometry.

SUMMARY

Proper interpretation of results is the largest single obstacle to successful application of holography. For example holographic interferometry now used for nondestructive testing of aircraft engine components might also be used in other industrial operations. These analyses, however, depend on the sensitivity of measurement or recording, correct readout of the holographic process, and, in particular, the ability to distinguish between the desired characteristics and any characteristics not of interest. A spurious characteristic ("noise") produces minute but systematic changes in the subject's surface that are faithfully translated by the holographic process into interference fringes, thus partially obscuring the fringes caused by the desirable event. The major challenge, then, becomes that of sorting out the desired holographic signature from the "false" signature (ch. 6). Such interpretations can be made only by people thoroughly grounded in both the fundamentals of the process to be analyzed and the details of the holographic tool being used. This knowledge usually comes only through experience.

In our eagerness to learn about and enthuse over spectacular current and projected applications of a developing technology, there is a tendency to forget the relatively unglamorous groundwork that has been done or remains to be done in developing and synthesizing new techniques and methodologies. Initial efforts to prove the feasibility of such new techniques often duplicate feats that have been accomplished before in a much simpler way, and early feasibility devices often lack the performance capabilities to complete the task they were designed for.

Two common errors can result. First, the potential may be overemphasized and the need to establish adequate foundations minimized, so that predictions for practical application are too optimistic and anticipate too short a development time. Second, an opposite overreaction may occur when developments fall short of the first rosy predictions. This can lead to unjustified pessimism about the new technology's practical value because of imagined insurmountable problems and physical limitations. Fortunately outlook and predictions usually become more realistic as more and more practical applications are developed.

The author believes that this cycle has already been experienced with laser technology and that holographic technology is still going through the pessimistic overreaction period. For example, laser performance in the early 1960's was inadequate to burn holes in anything thicker than balloons and razor blades, while holography fell far short of improving the resolution of electron microscopy—the task it was initially and so brilliantly conceived to do. Carbon dioxide and argon lasers are today welding together and drilling holes in respectable gauge metals and other materials. Holography was used just last year to improve the effective resolution of electron microscope plates.

In the interim, some scientists and engineers have had little faith in either. They first prematurely

TABLE III.–*Holographic State-of-the-Art*

Holographic Function	*R&D Status*	*Specific Use or Product*
Holographic Recording	CI[a]	Applications consultation laboratories
	CL[b]	Holographic photographic systems, plasma-physics holographic system
	D[c]	*Particle sizing holocamera, rocket, spray holocamera,* holographic x-ray radiograph system, furnace stack holocamera, wind tunnel holographic facility
	RE[d]	*Holographic nozzle turbulence and motion study*, nonconventional holographic recording materials study, human and cat's eye holography, fuel system holographic system, inline IR holograms
	RM[e]	*Holography of high velocity objects, recording materials measurement*, synthetic aperture hologram, hologram recording system, holographic image study, real-time holographic recording, multiple holographic recording
Holographic Display	CI	Holographic advertising displays
	CL	Three-dimensional display unit and viewer
	D	Dynamic hologram display screen, real-time three-dimensional display, calibrated holoviewer, holographic particle scanning and recording equipment, three-color hologram projection, holographic flight simulator, holographic TV display
	RM	*Holographic rendezvous simulation, visual holographic system, focused image hologram,* multicolor holographic map study, three-dimensional air traffic display concept
Motion Picture or Television Holography	CL	Holographic motion picture filming (scientific and entertainment)
	RE & RM	*Real-time motion pictures of holographic fringes, holography of thin film contamination*, motion picture holography
	RM	*Holographic fast-moving object motion picture concept,* holographic three-dimensional movie concepts
Holographic Microscopy	CL	Holographic microscope
	D	*Lunar surface holocamera*

Holographic Function	*R&D Status*	*Specific Use or Product*
	RE & RM	*Holographic microscopy in exobiology*, holographic microscopy of crystal growth
	RM	*Integrated circuit holographic microscopy*, total internal reflection holography concept
Holographic Interferometry	CI	Industrial holographic nondestructive test units, holographic tire tester, holographic height finder
	CL	Laboratory holographic nondestructive test system
	D	*Vibration mapping holographic system, holographic Schlieren wind tunnel system, holographic contouring system*, jet engine part testing holographic system, holographic turbine checking system, jet engine icing evaluation holographic system, holographic portable fringe control and *stabilization system*, gear tooth holography
	RE & RM	*Holographic subfringe measurement system, holographic fringe stabilization system, arc lamp holographic tester, holographic crack and fatigue detection, turbine blade interferogram system, optical element holographic test equipment, correlation between computed material stress and holographic interferograms, particulate contamination holography, heated panel vibrational holography*, internal engine cylinder fiber holography, switch gas flow holographic study, holographic radiation doseometer, modulated reference beam holography, infrared interferometry
	RM	*Pannel flutter holographic study, holographic turbine flow study, holographic interferogram interpretation study*, holography of crystal vibration, holographic speaker vibrational analysis, domestic burner holographic combustion study, holographic weak mine detection, holographic analysis of electron beam effects, holographic bomb detonation study, holographic analysis of composite plates and cylinders, automotive holographic testing study, holographic fringe localization study, holographic strain and deformation measurement, polarization holography, ball bearing holography
Microwave Holography	CI	Sidelooking synthetic aperture radars
	D	Holographic antihijacker system

Holographic Function	*R&D Status*	*Specific Use or Product*
	RE	*Short range microwave holographic imaging study, microwave holographic contour generator study*
Acoustic and Ultrasonic Holography	CI	Industrial acoustic holographic test units (nondestructive testing and medical studies)
	D	Holographic underwater viewing system, holographic reconstruction tube
	RE & RM	*Temporal modulated acoustic holography, Bragg cell pseudo-holographic system,* real-time three-dimensional acoustic holographic display concept, acoustic pseudo-holographic microscope concept
	RM	Direct acoustic holographic imaging system concept, medical acoustic holographic research, nondestructive acoustic holographic testing
Seismic Holography	RE & RM	Seismic holographic experimental system, seismic hydraulic hologram source
	RM	Earth mapping holographic concepts
Holographic Data Storage and Retrieval	D	Microhologram storage and retrieval system, holographic microfiche film viewer, holographic information retrieval
	RE & RM	*Holographic memory computer design program, holographic storage techniques,* digital data holographic storage system, holographic phototype composition storage concept, electron beam holographic storage equipment, holographic computer memory equipment
	RM	*Read/write holographic memory study,* holographic data storage for reconnaissance and surveillance study
Holographic Data Processing and Pattern Recognition	CI	Automatic holographic personnel verifier, holographic identity card system, synthetic aperture holography radar processor
	CL	Optical holographic correlator system, TV circuit holographic testing
	D	*Holographic solder joint correlator, coherent noise filter system*, hybrid holographic/

Holographic Function	*R&D Status*	*Specific use or Product*
		computer processing system, identification card holographic system, holographic geological oil processor
	RE & RM	*On-board holographic optical processor, holographic image deblurring equipment, holographic correlation spot mapping,* holographic fingerprint matching equipment
	RM	*Holographic processor input studies, holographic processing study, holographic tracking concept,* holographic ceramic characterization, holographic telescope concept, *meteor trail holographic processing*
Holographic Optics	D	Holographic grating, hologram lens
	RM	Aberration and dispersion computer calculations of holographic elements
Computer-Generated Holography	RE & RM	Computer-generated hologram system, three-dimensional photo computer-generated concept, computer-generated holographic optical processing filters, computer-generated interferometric test masters

[a]CI–Commercial, Industrial
[b]CL–Commercial Laboratory
[c]D–Development
[d]RE–Research Equipment
[e]RM–Research Methodology

relegated laser technology to the status of an interesting laboratory device; then they called holography, the stepchild of laser technology, only an amusing toy. Others kept working quietly, overcoming limitations and problems by their inventiveness and insight.

Today the practicality of laser technology is being demonstrated daily, and holography is on the threshold of general public recognition. Throughout, NASA has made and will continue to make important contributions to holographic development.

APPENDIX A

Why and How the Hologram Works

An excellent explanation of how a recorded hologram can reconstruct a three-dimensional image is based on the concept of a zone plate in optics (refs. 9 and 10).

Consider the simple hologram produced by a pinhole in the aperture plane shown (fig. 75) being illuminated by the plane wave incident from the left. An arrangement where the object is placed directly into the reference beam is called inline holography as distinguished from holography using a separate reference and object beam called sideband holography (figs. 4 and 5). The object beam can be represented as a spherical wave radiating out from the pinhole O while the reference beam is the undisturbed part of the plane wave incident on the hologram.

If the aperture plane becomes vanishingly small so that all that is left is a mathematical radiating point object and a coherent reference beam, then the nature of the interference fringes can easily be derived. Since the reference ray straight through the pinhole travels the same distance as either the object or the reference beam, the intersection of that ray with the film produces a bright constructive interference spot. The ray itself is called the axial ray. The cone of object rays at an angle $\Delta\theta_1$ with the axial ray will be just long enough so that they all destructively interfere with the reference rays to form the first dark fringe in the shape of a circle. The cone of rays at a greater angle $\Delta\theta_2$ with the axial ray produces the second dark circular fringe, and so on. In between each dark fringe circle there will be a bright constructive fringe; note that toward the outer edge of the pattern, the distance between successive fringes gets smaller and smaller. This pattern of circular dark and bright fringes is called a zone plate.

The zone plate is used as a substitute for a lens, and its chief property is to focus a plane wave of light striking it normally into a point at some distance along its axis (ref. 10). A schematic (fig. 76) is presented in the vertical cross-sectional plane containing the axial ray and illustrates this effect. Only the rays which, upon diffraction, constructively interfere at the focus spot pass through the plate. The rays that would have caused destructive interference by diffraction at the focus spot are blocked out by the dark fringes.

There is another important property of the zone plate. When illuminated by the plane wave, some of the energy or rays are deflected or diffracted in a diverging manner in such a direction that they appear to come from the point P'. This is called the "virtual image" of the zone plate. The rays forming the real and virtual images are diffracted at equal but opposite angles from the direct undisturbed beam direction (fig. 76). When these diverging rays are observed and some are collected by the eye at position E, one "sees" point P' as seen from above. If you moved your eye down to another section of the hologram at position E', you would still see P', but as seen from below. Point P' is called a "virtual image" because the observed rays do not pass through point P', while point P is called a "real image" because the observed rays do pass through it. In summary, the reillumination of the hologram zone plate by the same reference wave that formed it "reconstructs" a three-dimensional image of the original pinhole P. The reconstructed virtual image of point P is formed at its original distance from the hologram plate, and the conjugate real image P'' forms an equal distance in front of the plate along the axial line.

If only a portion of the original hologram is used (for example between breaks JJ'), the image of P' at E can be seen just as before, but it cannot be seen at E' because of the restricted field of view. This is true because every area of the zone plate hologram within the field of view recorded both the object and the reference beam. The real image formed at P will not be as bright, and its resolution will not be as high,

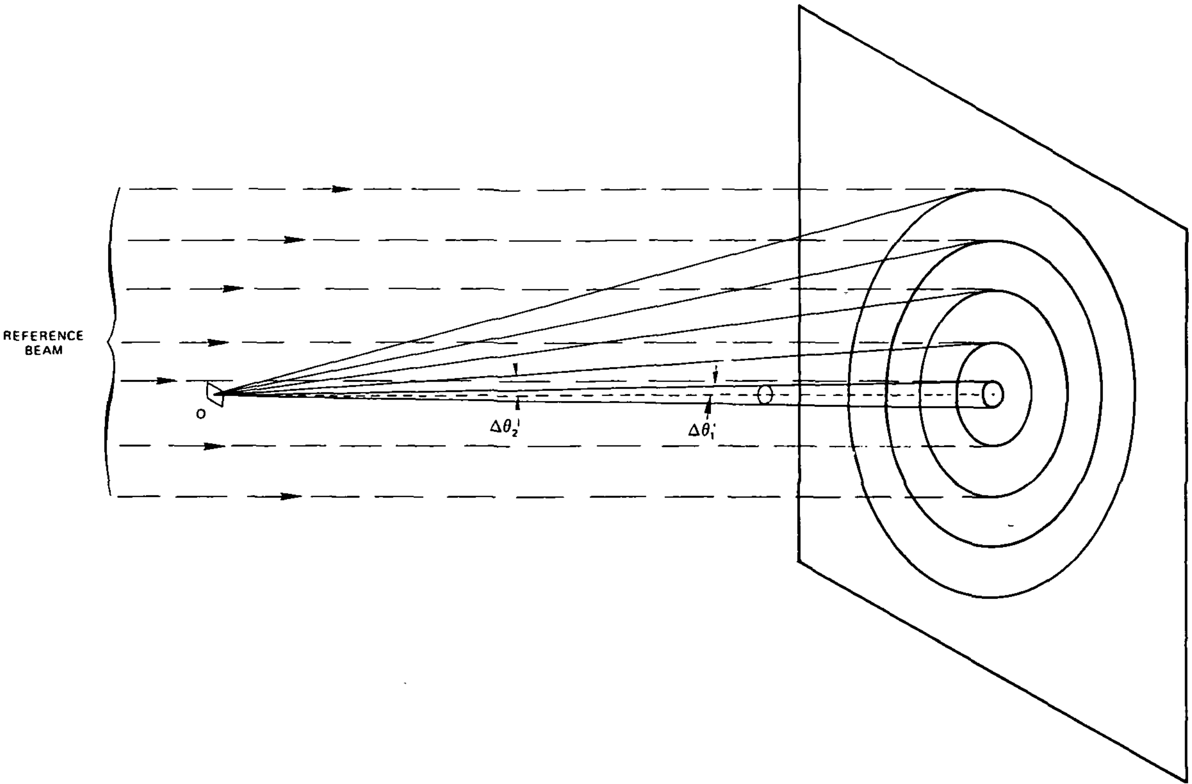


FIGURE 75.–Forming a hologram of a point object.

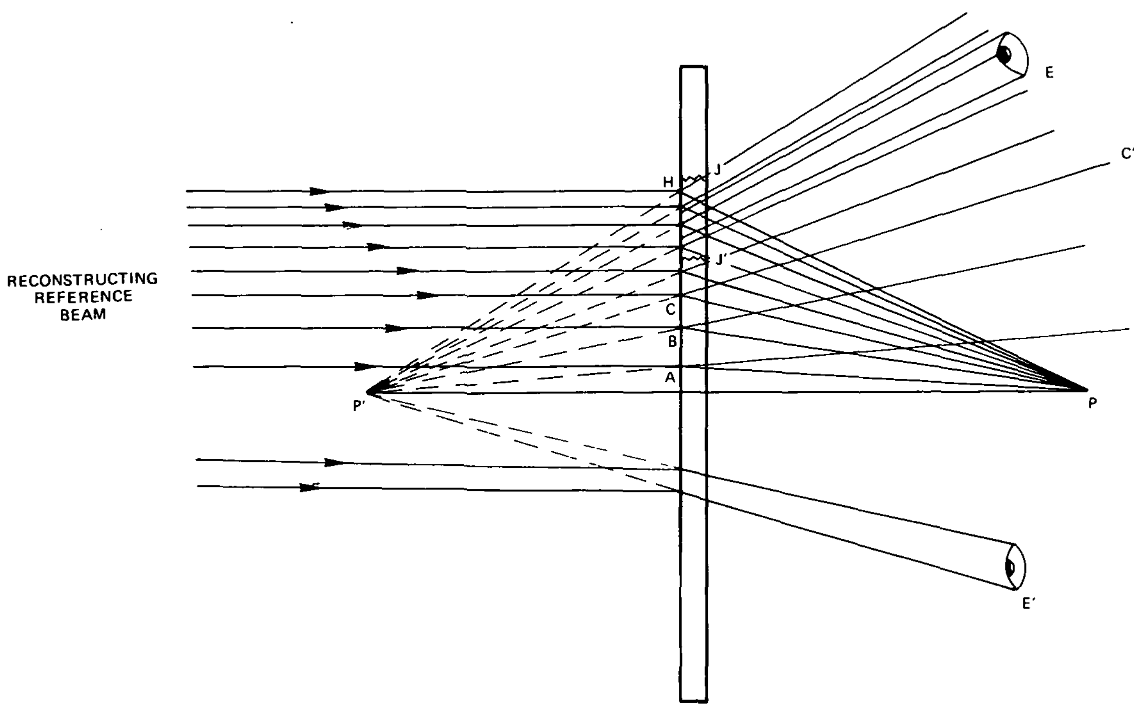


FIGURE 76.–Reconstructing point object hologram.

since only a small portion of the total rays forms its image (refs. 9 and 11).

Any object, no matter how complicated, can be made up of a sum of reflecting or scattering points in three-dimensional space. Hence when that object is coherently illuminated and a hologram is recorded, each point will form its own zone plate interference pattern. Consider the whole holographic pattern to be the superposition or integration of all the point zone plate patterns into a complex interaction pattern.

534-778 O-74—8

APPENDIX B

Hologram Mathematical Demonstrations

In this appendix the process of recording a hologram is developed mathematically, showing in detail how the virtual and real images can be reconstructed by using the offset plane reference wave. The discussion also demonstrates the reciprocity of the reconstruction process. A simplified notation is used in which upper case letters indicate complex quantities and lower case letters represent scalars. The complex quantities have a real and an imaginary part or component, while the scalars have a real part only.

It can easily be shown that the product of a complex quantity, Z, and its complex conjugate, Z^*, forms a scalar equal to the square of its absolute value. This mathematical property is used extensively in the following proofs.

The intensity of any light wave, a scalar proportional to its energy density, can be expressed as the product of its complex amplitude, A_L; and its complex conjugate amplitude, $A_L^* \cdot A_L$ can mathematically represent the phase and amplitude of a wave. Its real part, $|A_L|$, represents the amplitude of a wavefront, and its imaginary part, $e^{i\theta}$, represents the phase, θ, of a wavefront. Therefore

$$i_L = A_L \cdot A_L^* = |A_L| e^{i\theta} \cdot |A_L| e^{-i\theta} = |A_L|^2 \quad (1)$$

where the absolute or real value is indicated by the symbol $|A_L|$ (refs. 270 and 271).

The complex amplitude of the interference wave illuminating the hologram, A, can be represented as the sum of the complex amplitudes of both the reference wave, R, and the object wave, O; or A equals O plus R. Hence the intensity of the interference wave, i_h (another scalar), exposing the plate will be equal to

$$i_h = A \cdot A^* = (R + O)(R + O)^* = (R + O)(R^* + O^*)$$

Upon multiplying out the terms, we get

$$i_h = R \cdot R^* + O \cdot O^* + R \cdot O^* + R^* \cdot O \quad (2)$$

Now let $R \cdot R^* = i_r$; and $O \cdot O^* = i_o$, where i_r and i_o are scalars equal respectively to the intensity of the reference and object wave. Therefore equation (2) can be written as

$$i_h = i_r + i_o + R \cdot O^* + R^* \cdot O \quad (3)$$

It is possible to process the hologram film so that its complex amplitude transmission, T_h, will be proportional to the exposure or intensity of the interference wave, i_h. Therefore (ref. 272)

$$T_h = k \cdot i_h = k(i_r + i_o + R \cdot O^* + R^* \cdot O) \quad (4)$$

When the hologram is illuminated by the original reference wave, R, the complex amplitude of the reconstructed wave transmitted through the hologram is quite simply the product of R and T_h, or

$$R \cdot T_h = k(i_r \cdot R + i_o \cdot R + R \cdot R \cdot O^* + R \cdot R^* \cdot O) \quad (5)$$

Consider i_r and i_o as average macroscopic exposures. If the reflections from the object are completely diffused, then although there is microscopic interference fringe structure, the average density of the film as seen by the eye is very nearly equal across the entire hologram area for the i_o exposure. The reference wave is assumed to be a plane wave and its exposure, i_r, is also constant across the hologram. Equation (5) can be simplified making use of the relationship $R \cdot R^* = i_r$ to investigate the meaning of these terms.

PRECEDING PAGE BLANK NOT FILMED

$$R \cdot T_h = k \left[R(i_r + i_o) + (R \cdot R)\, O^* + i_r \cdot O \right] \quad (6)$$

The first term is just a constant $k(i_r + r_o)$ times the reconstruction complex amplitude R; this wavefront travels on through the hologram in the same direction as the original reference wave and is, therefore, called the dc term. The third term is the most interesting–it is a constant ki_r times the complex amplitude, O, or the original wavefront coming from the object to expose the hologram. Hence this reconstructed wave is diffracted from the reference beam by the hologram and travels in exactly the same direction and with the same relative amplitude as did the original object wave, O. Furthermore this wave, when viewed through the hologram, appears to be radiating from the object and cannot be distinguished from the original object wave form. This wavefront forms the virtual image of the object.

The second term is harder to interpret, but it can be seen to be the conjugate of the complex amplitude of the object wave modulated by the term $k(R \cdot R)$. We have already seen that the O complex amplitude represents the original wave spreading out or diverging from the object; we can also show mathematically that its complex conjugate amplitude, O^*, represents a wave focusing down or converging into the object. Therefore it represents the real focused image of the object. This reconstruction of the real image, however, generates image aberrations because it is modulated by the term $(R \cdot R)$ that has some phase characteristics.

We will now show that if we can find a way of illuminating the hologram with the complex amplitude R^* instead of R, a real image free of aberrations is formed. For example if R is a plane wave incident in some direction θ to the hologram axis, it can be designated as $R = |R|\, e^{i\theta}$; then R^* will be a plane wave incident on the hologram from the rear along the same line but in a directly opposite direction, $-\theta$, or $180^\circ - \theta$. The wave front R^* can then be designated as $R^* = |R| e^{-i\theta}$. When R^* illuminates the hologram, the complex amplitude equal to $R^* \cdot T_h$ will be formed; or taking R^* times equation (4) we have

$$R^* \cdot T_h = k \Big[i_r \cdot R^* + i_o \cdot R^* + R^* \cdot R \cdot O^* + R^* \cdot R^* \cdot O \Big] \quad (7)$$

or

$$R^* \cdot T_h = k \left[R^* (i_r + i_o) + i_r \cdot O^* + (R^* \cdot R^*) \cdot O \right] \quad (8)$$

Now it can be clearly seen from the second and third terms that the real image O^* is perfectly reconstructed, as is a modulated version of O (the third term). This is the preferred way of reconstructing the real image of the object, and it is positioned about the reflected center of the original object if the hologram has not been moved.

These same equations can easily demonstrate the reciprocity of the reconstruction process. Consider what happens when the hologram of equation (2) is illuminated not by the reference wave amplitude, R, but by the wave transmitted through or reflected from the original object, O. By forming the product $O \cdot T_h$, a second modification of equation (5), the modified terms of equation (5) are

$$O \cdot T_h = k \left[O(i_r + i_o) + (O \cdot O^*)\, R + (O \cdot O) R^* \right] \quad (9)$$

The first term is the reconstruction object wave modulated by the constants $(i_r + i_o)$; the second term is the reconstructed reference beam modulated by the constant, i_o; while the third term is related to the complex conjugate of the reference wave. The reconstructed reference wave can be focused down to a correlation spot and is the basis for correlation matched filtering.

Now imagine that the reference wave, R, is not a plane wave but a wave reflected from a second object, O_2. Consider that the illumination of the original hologram was formed by $O_1 + O_2$ rather than $O + R$. All the equations we have derived so far hold if we transform the complex amplitude, R, into O_2 and the complex amplitude, O, into O_1.

Let us now examine the reconstruction we have calculated in equation (9) in light of this transformation. The illumination by O_1 has resulted in the reconstruction of the virtual image, O_2. The first series of illuminations by O_2 and O_2^* (equations 6 and 8) resulted in reconstructions of O_1 and O_1^*. It follows that illumination by O_1^* results in the formation of the real image of O_2^*. Thus the reconstructions are reciprocal relationships, and this fact can be made the basis for either correlation filtering or coding (ch. 9) (ref. 273).

APPENDIX C

Hologram Classifications and Performance Parameters

This appendix discusses the eight classifications of holograms mentioned in chapter 2 and describes principal performance parameters used to characterize all types of holograms.

CLASSIFICATIONS

Transmission/Reflection Mode Holograms

A hologram must be recorded in either a transmission or a reflection mode, indicating different exposing geometries. If the object to be holographed does not transmit light, the reflection mode must be used; if it does, either mode can be used, depending upon the application. For example in thin film and particle contamination monitoring, the reflection mode gives information about the surface particle deposits, while the transmission mode provides information on the thin film layers (ch. 6).

These two exposure modes can be further subdivided into diffusely scattered transmission object beams, diffusely reflected object beams, nonscattered transmission object beams, or specularly reflected object beams. The diffusely reflected or scattered object beam ensures the property of fragmentation and redundancy so important to data storage and display applications, but the price paid for this redundancy is a speckle pattern in the viewed reconstructed image. This speckle appears as excessive graininess like that observed in enlargements from fast photographic film. It can be reduced by using large aperture lenses to replace the small aperture human eye during the reconstruction phase, by mechanically moving displays, or by dynamic electric displays (ch. 4) (ref. 274).

The terms transmission and reflection hologram are also quite often applied to the reconstruction of a hologram rather than to its recording. In this case a transmission hologram means one whose reconstruction forms an image by transmitting the reference beam through it, while a reflection hologram forms its image by reflecting the reference beam from its surface, or from interior surface planes in the case of a thick volume reflection hologram.

Thick/Thin, Volume/Plane Holograms

Holograms are also classified according to the thickness of the recording medium into thick and thin or volume and plane holograms. As the names imply, these categories are based on the effective active depth or thickness of the recording material compared with the wavelength dimension. Throughout much of the earlier discussions, we have been describing the holographic process as essentially the recording of an interference fringe pattern on the surface of film. But if the material or emulsion is thick and relatively transparent to the illuminating radiation, these interference fringes are produced not only on the surface but also throughout the volume of the emulsion. When the emulsion is developed, a set of three-dimensional layers is then formed within the emulsion, corresponding exactly to the positions of the illuminating interference fringes.

Figure 77 illustrates this effect for both object and reference point sources. The three-dimensional interference fringes throughout the volume of the media are represented by the dotted lines. As illustrated by figure 77b, upon reconstruction the developed density layers act as planes throughout the volume of the emulsion. Essentially, they reflect energy only in those directions where the angle of reflection can equal the angle of incidence (the simple mirror law of optics).

There must also be a definite relationship, called the Bragg condition, between wavelength, λ, interfringe plane spacing, d, and angle of incidence, θ, if the reflections from neighboring planes are to add

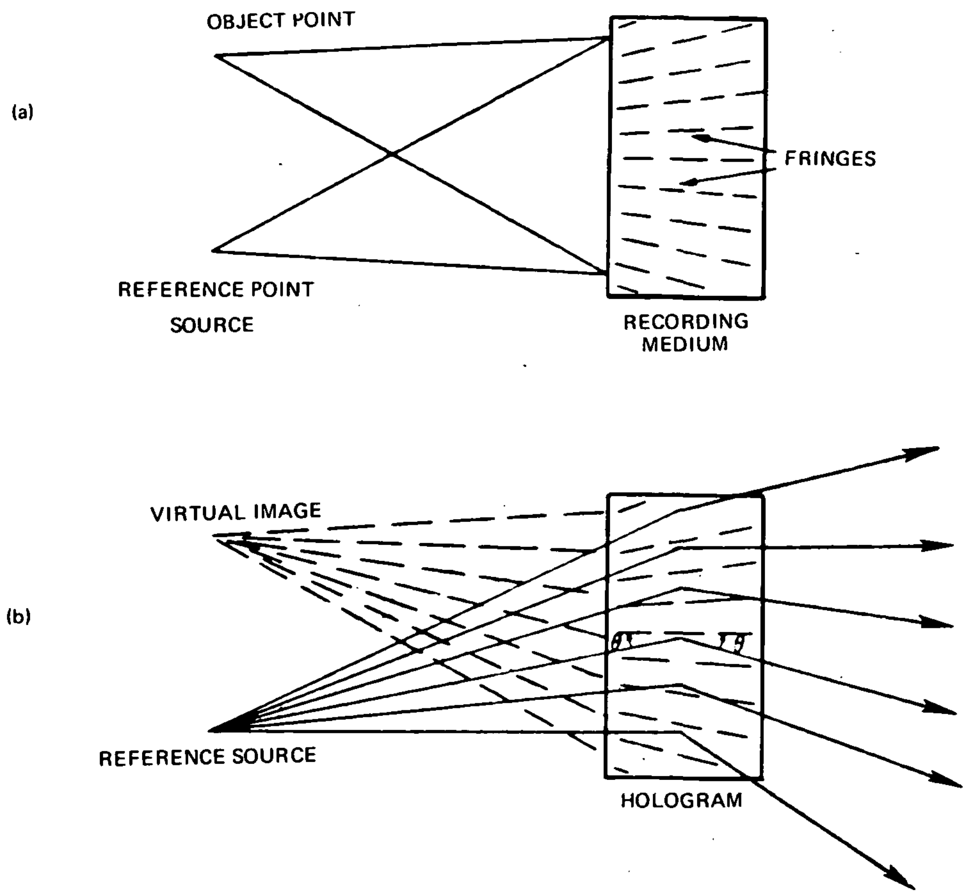


FIGURE 77.–Formulation and reconstruction of volume (thick) hologram.

together coherently. This Bragg condition is given by the equation

$$\theta = \cos^{-1} \lambda/2d$$

Figure 78 illustrates this for the case of straight line fringes formed (fig. 78a) by interference of an object and reference plane waves. Only the rays of wavelength λ_1 will be constructively reflected at the proper angle (as indicated by rays labeled 3, fig. 78b) when illuminated by white light at incidence angle of θ to the fringe planes. All other wavelengths will be observed or scattered.

Another very important effect of these reflecting planes in the volume hologram is to increase the diffraction efficiency of images formed by the reconstruction illumination, since in general the Bragg reflection process is far more efficient than the usual diffraction or scattering process in optics (refs. 275 and 276).

Color/Monochrome Holograms

Since one set of three-dimensional interference planes can be formed by a single wavelength exposure in the emulsion, there is no reason why a second monochrome exposure at the same wavelength, made later on the same volume of emulsion, could not form a second series of interference planes. If the angle of this second set were made substantially different from the first by changing the reference beam orientation, then reconstruction crosstalk would be minimized because the respective reference beams, when sequentially illuminating the hologram, only reconstruct from their own associated sets of Bragg reflecting planes.

This is the basis for storing multiple superimposed monochrome images for efficient data storage; it can also be used to provide color separation negatives required for three-dimensional color picture projection. Each three-dimensional color negative illumi-

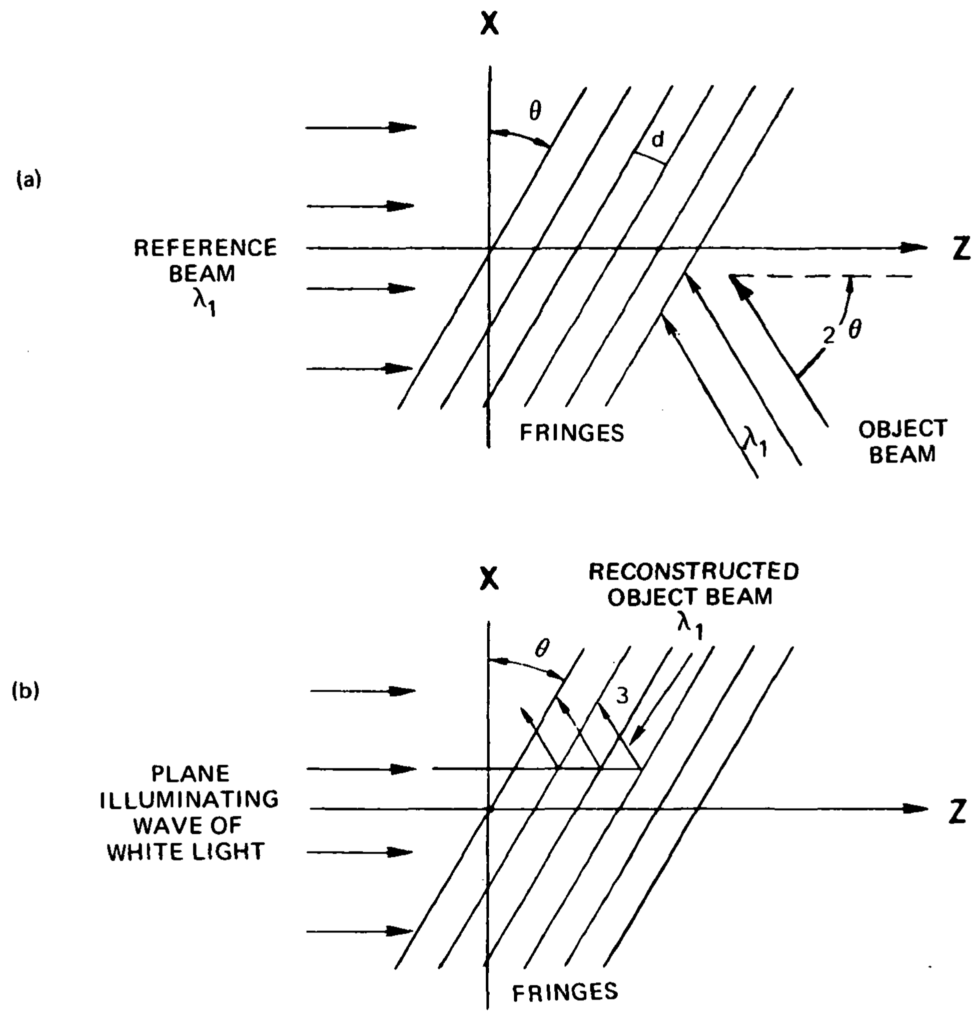


FIGURE 78.–Fringe formation, reconstruction by Bragg reflection.

nates the hologram from a different angle. If the multiplex recording illumination is carried out by three different monochromatic wavelength beams, then the direction of the reference beams between successive multiplexed exposures need not be changed–in fact the exposures can be performed simultaneously. Each color then produces reflection planes of the same angular orientation but with different spacing and intensity in the hologram; and each set of planes in turn can be sorted out properly during the reconstruction, since only its associated color provides the necessary conditions for strong reflection. This selectivity is so good that the thick multicolor hologram can usually be illuminated from the back by a strong incoherent white light source to form a high resolution colored three-dimensional image (ref. 277).

Optical/Microwave/Acoustic/Seismic/ Computer Holograms

Holograms are sometimes categorized in terms of the type of radiation, wave disturbance, or equipment used to form them. "Direct" holograms are produced by wave interference, while the pattern of "indirect" holograms is calculated by high-speed computers. Computer calculations specify the position, shape, and size of a synthetic array of apertures which when illuminated by the reference wave will reconstruct the desired object. This object need not be real. The array

of apertures is either duplicated on film or fabricated into some other material to form the "computer hologram." Usually these apertures are binary holes, but they can be made of varying density material (ref. 278).

This survey is primarily concerned with optical holograms, although all coherent forms of radiation can form holograms. Techniques exist for building up holograms from incoherent photographs or radiation recordings. Because nonoptical radiation holograms can record directly the amplitude and phase of fringes from objects, the reference beam is not always used during recording. In fact the synthetic aperture sidelooking radar really exhibits a perfect application of one-dimensional holography as it records microwaves reflected from the terrain (ch. 8). Microwave holography actually predates coherent optical holography using lasers. It was developed about the same time that Dennis Gabor made his remarkable discoveries using incoherent sources in 1948 and 1949.

Amplitude Phase Holograms

We have already seen how only the phase change of either the reference or the object beam can cause changes in the fringe interference pattern recorded on the hologram material (ch. 2). It is reasonable to expect that changes of either amplitude, phase, or both in the reconstruction beam can be used to form virtual or real images for display and measurement, and this is in fact the case. The hologram affecting primarily the phase of the illuminating beam is called a phase or phase-only hologram. This phase shift is developed by a change in either the thickness of the material or its index of refraction. Both occurrences effectively change the optical path length of the beam through the material at various plate positions, and hence cause phase diffraction of the reconstruction beam. If the material can be made nonabsorbing, then greatly improved diffraction efficiencies are possible.

Most holograms, however, are composed of absorbing layers or volumes which diffract the reconstruction light beams through differential absorption into the proper images for viewing. The spatial modulation of the hologram's amplitude transmission is usually easier to produce and control than the phase transmission and so far has resulted in the maximum resolution obtainable.

When amplitude holograms are reconstructed, spurious phase changes caused by thickness variations in film or sensitive layers (either present before or produced during development) are particularly troublesome. Most of these material variations can be eliminated by using a "liquid gate" during projection. In the gate, the film recording the amplitude hologram is immersed in a tank of liquid whose index of refraction matches the index of the film. The total effective thickness of the combination then remains constant even if the film thickness varies; hence all wave modulation is caused only by density changes. These liquid gates are complex and expensive, however, and do not allow rapid film movement.

The amplitude modulation process for thin holograms is extremely inefficient because, in general, only 1 or 2 percent of the illuminating radiation is diffracted into the reconstructed image. Diffraction or reflection from the thick, amplitude modulated volume hologram is better but can still stand much improvement.

Time Average/Single or Double Exposure Holograms

Time average holography (ch. 6) is the continuous exposure of reflections from a vibrating object. The object usually goes through several vibration cycles during the exposure time, and continuous wave lasers can be used.

In double-exposure holography, two wavefront recordings are made on the same film. When it is illuminated, the two sets of interference fringes representing each exposure form "interaction" fringes of their own. The separate interference fringes are often too fine to be observed, but the interaction fringes can be seen quite clearly and give a vivid representation of the geometric changes produced on the object between the two exposures. Normally, the object is subjected to various types of pressure, temperature, density, or force stress between exposures, but many other types of movement or material accumulation can be observed. For example a fast growing plant might exhibit movement due to growth or oscillation between two time-lapse hologram exposures.

Single-exposure holography, also called real-time holography, involves a stationary, usually unstressed object. After development, the hologram is placed in the same location where it was exposed (this position must be accurate to a fraction of a wavelength) and lighted by the same reference beam. Looking through the hologram, the observer then sees both the

reconstructed virtual image and the real object exactly superimposed. If the object is slightly stressed, such as by the pressure of a finger, interaction interference fringes can immediately be seen (in real time) between the object and its unstressed image. Movement of the hologram plate will produce still another fringe pattern. This technique is useful for setting up experiments and measurements before actual photographs are made, and is also the basis for obtaining motion pictures of fringes caused by dynamic motions of the object (ch. 7).

Sideband/Inline Holograms

The geometry of hologram production (sideband or inline) has a striking effect on the nature of the hologram and on its properties during both formation and reconstruction. The principal categories of sideband holograms are Fourier transform and Fresnel holograms. These classifications and their subcategorizations probably determine the usefulness of a hologram to a greater extent than any characterization so far discussed.

Inline and sideband holography are characterized by their inability or ability to separate out the virtual and real images so that they do not interact and can be separately observed. We can think of this separation as being accomplished in sideband holography by modulating the virtual and real image spatial video information on two different high frequency band carriers. This is done by using an object beam and a reference beam to illuminate the hologram plate from two different directions (figs. 4 and 5). Subsequently the two images can be separately recovered through proper filtering of the reconstructed carrier signals.

In the sideband hologram technique, the carriers are actually spatial frequencies, and the demodulation process of separating out the two types of images is accomplished by directing the virtual and real image signals into different directions. The two separate sets of reconstruction lenses at the eyeball's different point of observation can then be considered as spatial filters that accept only the proper range of spatial frequencies (refs. 279 and 280). Interference between these waves on the hologram is similar to mixing these various frequencies together to form sum and difference frequencies (refs. 281 and 282). The interference fringes are just the beats of the different frequencies, while the nonlinear terms that also result from the nonlinear t/E characteristic curve of the hologram are the harmonics of the sum and difference frequencies.

Appendix D develops in further detail the correspondence between spatial frequency components and directions of propagation in optical systems (refs. 281 through 284).

Fourier transform hologram: A wave focused in the back focal plane of a transform lens has both an amplitude and a phase. A Fourier transform hologram is made by the interference between the amplitude and phase (complex amplitude) of the frequency spectrum waves in the transform plane and a plane reference wave. An important characteristic of the Fourier transform hologram is that it places a minimum spatial frequency requirement on the recording material. However, the dynamic range of the interference wave's intensity can be very large indeed with such an arrangement. This means that when such holograms are used for matched filtering (app. D), great care must be taken in their exposure, processing, and development.

A stringent condition on the Fourier transform hologram is that it must be formed by a plane object or transparency; therefore this type of hologram is used only for data storage or optical processing. Motion by the object in the front focal plane of the transform lens during hologram exposure does not cause any change in the amplitude of the image in the back focal plane. This property of Fourier transform holograms has been applied to holographic motion picture projection and holography of moving objects (ch. 7) (ref. 285).

Fresnel hologram: Another form of sideband hologram useful for all types of objects and applications is the Fresnel hologram, which gets its name from the fact that it is recorded without any lens and is placed very near the object. The plate records the "near field" diffraction pattern, called the Fresnel diffraction pattern of the object. Although these holograms are quite easy to form, their chief disadvantage is the wide band of spatial frequencies that must be recorded by the plate.

A third type of sideband hologram is the focused image hologram. The NASA scientists who originally discovered the principle behind its construction predict that it will be useful in relaxing constraints on the coherence and size of the source needed to reconstruct and produce a hologram (ch. 3).

Inline holography is sometimes used to simplify

the optical recording process. Using only a plane reference wave, the diffraction pattern of an object, such as a series of small particles, can be recorded at an "infinite distance" from the hologram plate (called Fraunhofer diffraction). Such a recording is an inline hologram (ch. 3). When this hologram is reilluminated, the real image contribution is so defocused that it appears only as a very slight uniform additional dc intensity component added to the virtual image diffraction pattern. Fortunately, finite distances can often satisfy the "infinite distance" or far field distance requirements in practical situations.

The far field distance is expressed as proportional to the ratio of the squared radius of the object particle to the wavelength of exposing light (ref. 20). The far field condition can also be realized by placing a lens beyond the particle's diffraction pattern to focus the pattern onto the recording medium. The Fraunhofer diffraction pattern or far field diffraction pattern is formed in the back focal plane of the lens. Inline holography is sometimes called Fraunhofer holography, and inline holograms, Fraunhofer holograms.

HOLOGRAM PERFORMANCE PARAMETERS

The most important measures of hologram performance are connected with the characteristics of the reconstructed virtual and real images. As might be expected, these characteristics are also intimately related to the media upon which the holographic interference patterns have been recorded. The final appearance of reconstructions is of course also constrained by the nature and quality of the recorded pattern. If the holographic system setup has been carelessly designed so that, for example, the spatial fringe resolution exposure requirements exceed the resolution capabilities of the recording media, degraded resolution image will result.

Diffraction Efficiency

The brightness of the reconstructed image is important for viewing because the eye can seldom resolve all the resolution capability inherent in the recording medium; it usually judges the quality of a reconstruction by the brightness of the projected image. Image brightness is determined by the power density of the illuminating source and the diffraction or reconstruction efficiency of the developed hologram. The reconstruction efficiency is defined as the ratio between the amount of power diffracted or projected into the viewed image and the total amount of power in the incident beam striking the hologram. The square root of this efficiency is equal to the ratio of amplitudes between the diffracting and illuminating wave, and it is important to keep this ratio linear. If this amplitude ratio becomes nonlinear during an exposure, then all sorts of image perturbations, distortions, and aberrations take place during reconstruction (ref. 282).

Efficiency/Recording Ratio/Exposure Tradeoff

Figure 79 clearly shows the complexity and interaction of the important parameters of exposure (E), and the ratio of recording reference to object beam intensities (R) that determine the diffraction amplitude efficiency ($\sqrt{\eta}$) of the reconstruction. A separate set of these diffraction efficiency characteristic curves must be developed for each recording material, and modifications to the actual magnitude of the curves must be determined by the nature of the scene recorded on the hologram. The curves of figure 79 are based on idealized plane wave object and reference beams.

Exposure

The need to determine exposure accurately is obvious, since both underexposure and too high an exposure cause loss of efficiency. This occurs especially as the recording beam ratio approaches unity, which normally is expected to give the highest values. Figure 79 clearly shows the critical nature of the exposure value necessary to obtain a linear relationship between the square root of the reconstruction efficiency and the fringe visibility. Only the exposure curve labeled E_3 appears to satisfy these conditions (ref. 286).

The need to record in the linear characteristic region also constrains the relationship between the intensity of the light producing the hologram exposure and the length of exposure time. Since the expected motion of the object to be holographed very strongly dictates the range of exposure times to be tolerated, the power output of the laser source must be great enough to provide the necessary light beam intensities on the hologram. Fast-moving ob-

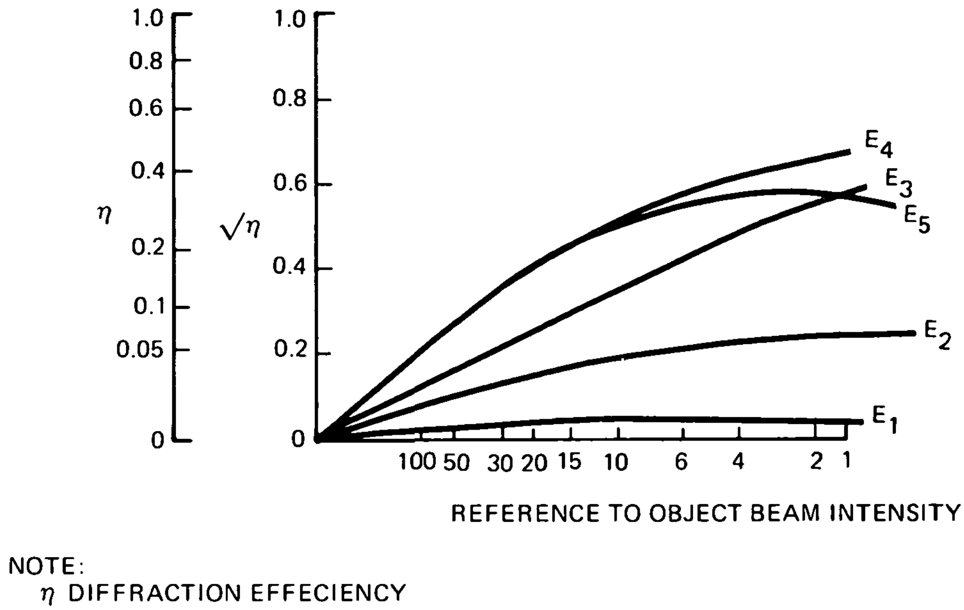


FIGURE 79.–Diffraction efficiency characteristic curves.

jects requiring pulses as short as 5 to 25 nanoseconds put the most demand on high power lasers, which are, of course, more complex and expensive. The wide range of sensitivities associated with the various recording media and is presented in table 4.

Resolution

The final resolution of a projected or viewed image depends upon a rather complex tradeoff analysis between these major factors: the nominal *f/n* of the recorded hologram, the effective aperture of the hologram exposure, the aberrations in the reconstructed image, and the speckle grain size in the image. The maximum theoretical diffraction limited resolution is obtained from the nominal *f/n* of the hologram, equal to the ratio of recording distance to diameter of hologram plate (fig. 80). The smaller the *f/n* the higher the resolution (ref. 287). However, the effective diameter of the hologram is sometimes reduced at the edges of the plate where the recorded fringe frequencies are apt to be highest. If the resolution capability of the recording material is exceeded, then that part of the hologram is washed out and the effective diameter and hence hologram *f/n* decreases proportionately.

The geometric arrangement of the object and the reference beam greatly affects the maximum spatial fringe resolution which must be handled by the hologram recording material. Recall the first illus-

TABLE IV.–*Properties of Holographic Recording Media*

Recording Medium	*Typical Resolution, Lines/mm*	*Typical Exposure Required, ergs/cm²*	*Absorptive (A) or Phase-Only (P)*
Photographic Emulsions	Over 2000	$20\text{-}10^3$	A and P
Photochromic Materials	Over 2000	$10^4\text{-}10^7$	A
Photopolymer Materials	Over 1000	$10^4\text{-}10^6$	P
Thermal-Plastic Materials	1000	10-100	P
Dichromate-Sensitized Gelatin	Over 2000	10^5	P
Electrooptic Crystals	Over 4000	10^9	P

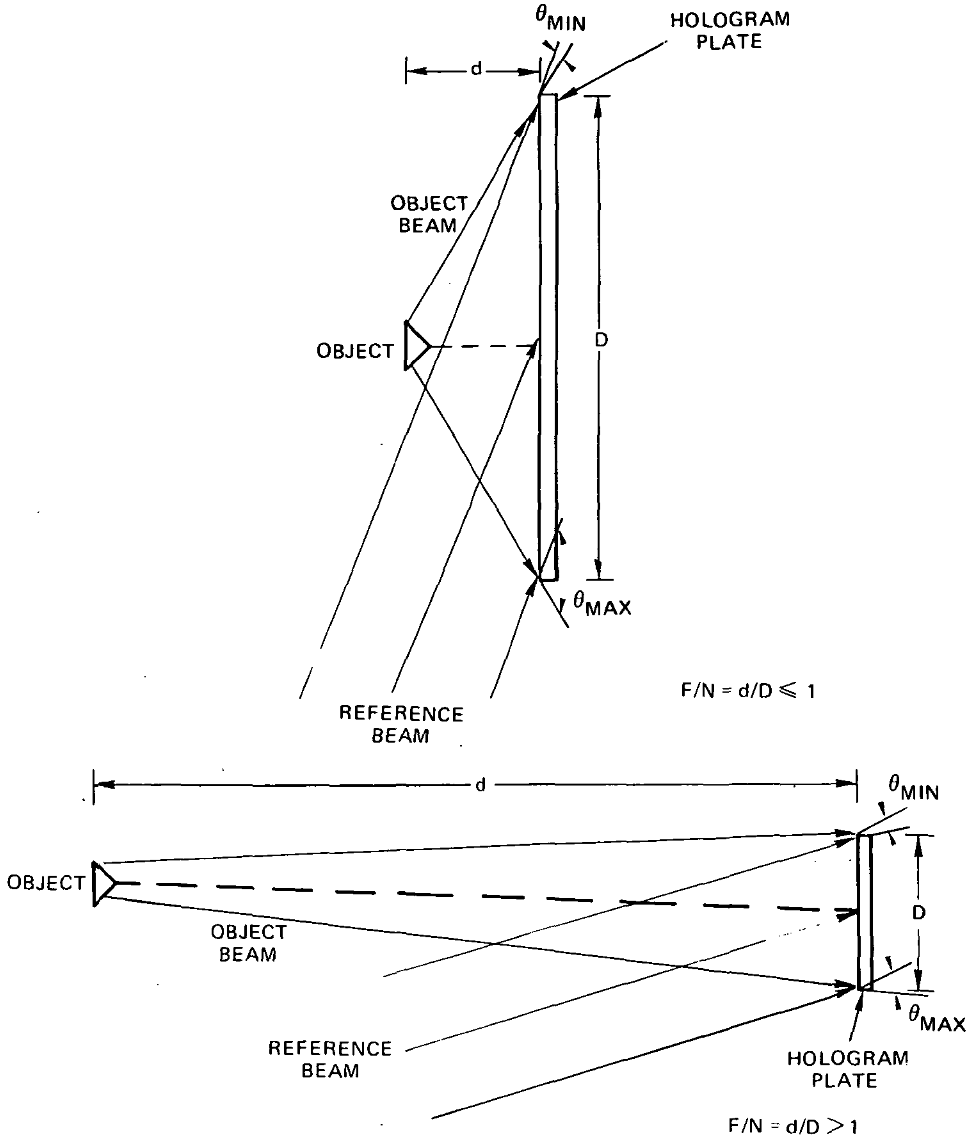


FIGURE 80.–Hologram *f* number variation.

tration of the hologram formed by the two plane waves (fig. 1); if the angle between the object and reference beams is increased, then the spatial frequency of the interference fringes increases and hence the resolution requirements of the film or recording material increase comparably. The resolution requirement can be quantitatively expressed by the simple equation

$$f_r = \frac{2 \sin (1/2)\ \theta^*}{\lambda}$$

where f_r is number of line pairs per unit of length required to be recorded by the material; λ, the wavelength of the recording light, and θ, the angle made between the reference and object beam. When one beam is normally incident upon one side of the media and the other beam is normally incident from the back side, the spacing angle θ is maximum and equal to 180°. In this case the required resolution is a maximum and equal to $2/\lambda$ line pairs per unit of length. This geometry is frequently used when making thick volume holograms (ref. 6).

Figure 80 clearly shows the relationship between hologram *f/n* and the required fringe resolution *f/r* through the angle θ between the direction of the reference beam and the object beam. Note how the large *f/n* hologram results in small angle θ and little variation between θ_{MAX} and θ_{MIN}. From the equation above this means the resolution to be recorded is low. The small *f/n* hologram illustrated at the top (which will give the maximum projected resolution) requires a high fringe resolution to be recorded at its bottom because of the large value of θ_{MAX}. Some material might not be able to record such a high resolution, and part of the hologram would be ineffective in projection.

The effect of discrepancies between the recorded and reconstructed geometry and the departures from plane wave reconstruction illumination will often introduce into the projected image the usual third-order optical system image aberrations, causing a further decrease in the resolvable elements per unit length in the projected image. The number of resolvable elements in the reconstructed image is inversely proportional to the wavelength of the illuminating source and the effective *f/n* of the hologram. Final image resolution loss might be introduced by excessive diffuse scattering that could cause speckle-noise grain sizes greater than the aberration resolution limits. Careful design of the equipment setup or the use of compensating lens and display units can usually overcome these speckle effects (ref. 287).

Finally, table 4 shows the major limits on exposure and resolution capabilities of the major holographic phase and amplitude recording media being currently studied and developed for practical use (refs. 288 and 289).

Page Intentionally Left Blank

APPENDIX D

Holographic and Optical Data Processing Principles

OPTICAL SPATIAL FREQUENCIES

We will use figure 81 to illustrate how it is possible to analyze any optical image into its two-dimensional spatial frequency components. The basis of the demonstration is the concept that a bundle of parallel rays propagating at different angles with the optical axis represents different spatial frequencies, and that the greater the angle from the axis the higher the spatial frequency content.

Consider the interception of two bundles of plane waves of this type which are traveling in directions defining a vertical plane containing the y axis (fig. 81a). We have already seen (ch. 2) that they produce interference fringes that are evenly spaced horizontal lines parallel to the x axis (fig. 1). It is a well-known geometrical optical property that a perfect thin lens focuses all of a parallel bundle of rays to a point defined by the intersection of the ray passing through the center of the lens with focal plane. Thus the bundle directed down at some angle B from the axis (fig. 81a) focuses into the spot labeled $-f_1$ on the y axis, while the upwards directed wave bundle, also at angle B, focuses at the spot labeled $+f_1$ on the y axis.

It is also a well-known principle in optics that a perfect lens images in its back focal plane the two-dimensional spatial frequency spectrum (or two-dimensional Fourier transform) of any image located in its front focal plane. This is a remarkable property of a lens extensively used in Fourier transform holography and optical data processing. The spatial frequency spectrum in the transform plane is normalized so that the dc frequency component, the rays parallel with the axis, is focused right on the optical axis, while the higher frequency components are focused on circles of increasing radius from the axis. The polar directional displacement from the axis is related to the angular direction of propagation of the spatial frequency components making up the image (ref. 290).

OPTICAL TRANSFORMS AND FILTERS

The concept of an optical image being made up of spatial frequency components in two dimensions is extremely useful; it aids understanding of all optical filtering and optical data processing operations. Just as the audio output frequency characteristics of a high fidelity sound system can be expressed as the product of the amplitude and phase of the frequency components contained in the stereo tape or record with the frequency and phase response curves of the hi-fi system, so the output spatial frequency characteristics of an optical system are equal to the product of the amplitude and phase of the spatial frequency components of the object image with the spatial frequency and phase response of the optical system.

The complete specification of the response of an optical system is called the optical transfer function. As implied above, it is made up of two parts: the modulation or amplitude transfer function and the phase transfer function. Any distortion or aberration of the image formed by an optical system can be expressed by an appropriate form of the amplitude or phase response of the system. An optical transform function can express not only the effect of lens aberrations on a normally focused image but also effects due to lens defocusing, object motion, scintillations, and refractive inhomogeneities along the optical path.

Separate components of an optical system cascade or multiply their frequency response curves together and add their phase responses together to form the total system output. If one of the components of an optical system is a transform lens and the other an optical filter, consider the cascading operations possible when the filter is placed in the transform or Fourier frequency plane. In the simplest case, the filter can be an opaque plate with a small hole cut out to allow only a few of the component frequencies to pass through. The modulation transform function of

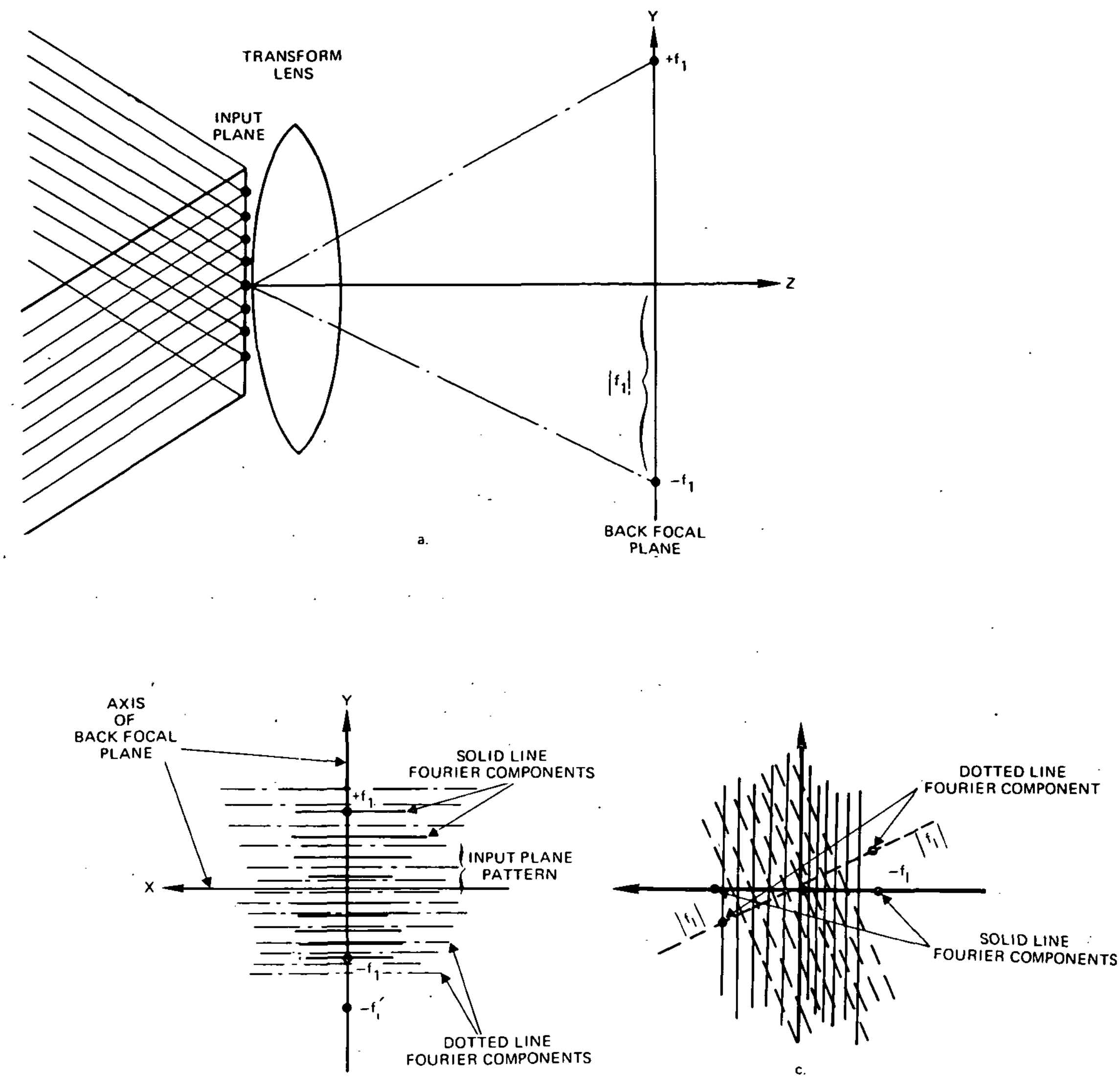


FIGURE 81.–Spatial frequency principles.

the filter can then be plotted to appear as a narrow pulse of amplitude unity in the regions represented by the hole, with background amplitude of zero at all other frequencies. Such a filter is called a bandpass filter or a blocking filter.

By producing the proper transmission as a function of position, any amplitude modulation transfer function can be synthesized. If the filters were made of concentric rings about the axis of varying transmissions, then the filter frequency response would become independent of the input image's orientation. Filters of this type are being developed for image evaluation processes (ch. 9). If instead of having a variety of densities the rings are varying thicknesses of transparent material, then phase shifts rather than amplitude changes are produced by the filter, and various phase transfer functions can be synthesized. However, the simultaneous control of both amplitude and phase of a film or plate was very difficult before the advent of holography, and all practical filtering involved only simple blocking or spatial frequency attenuation filters. Correction for deblurring, lens aberrations, or other types of image distortions by optical filtering was very imperfect, since the degrading phase effects of the object and the correcting optical system could not be compensated for.

Holography has changed this. Holograms opened up the possibility of recording on a photographic film or other light-sensitive surface both amplitude and phase or complex transform functions. The original discovery made by VanderLugt at the University of Michigan* consisted of recording a Fourier transform hologram by imaging the object function through the transform lens onto the hologram using a normal off-axis reference beam setup. Such a filter or hologram has the remarkable property of representing a complex filter only by its absorption qualities, not its phase perturbing characteristics (ref. 291); therefore this filter can be placed in a liquid gate to eliminate spurious phase effects. These holographic complex filters can be used to perform deblurring, image enhancement, and correlation filtering (refs. 292 and 281).

Holographic Matched Filtering or Correlation Function Measurement

Figure 82 shows how a Fourier transform hologram of an unstressed solder joint is made, developed, and then placed back in its original position for filtering. If this unstressed solder joint located on the test material board is again illuminated by the laser, its Fourier transform image wavefront will be incident upon the hologram filter, as shown by the dotted lines in the figure, making the wavefront identical to the original object wave that formed the first Fourier transform hologram. Since the hologram is illuminated by its object wave, its reference wave will be reconstructed** (app. B). Because its original reference wave was a plane wave off axis, the reconstructed wave will also be a plane wave off axis focused by a lens to a spot on the photo multiplier tube as shown in the figure. The intensity of this spot will be equal to that produced by the original reference wave. Consider its value as a normalized maximum of one unit; the value of unity represents the maximum value of the autocorrelation function of the spatial frequencies of the unstressed joint with itself.

However, to measure the change of the stressed solder joint from its original unstressed form, a slightly different procedure is required. The hologram must be illuminated with the image of the thermally

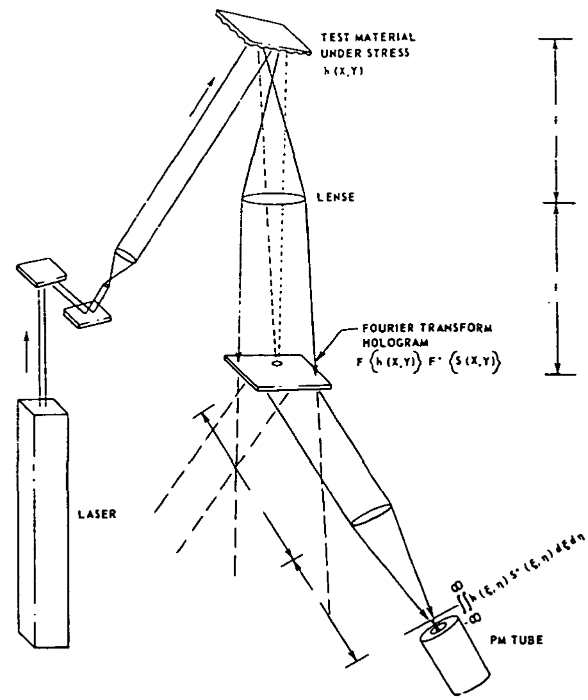


FIGURE 82.—Configuration for measuring deformations by Fourier transform holography.

stressed solder joint after it has returned to equilibrium temperature. Instead of reconstructing a perfect reference wave replica, only a part of the reference wave is reconstructed, and the intensity of the spot on the PM tube will be less than unity. This decrease of intensity can best be understood by saying that the parts of the illuminating new object wave that are exactly like the original object wave will reconstruct a portion of the reference wave as before, but since there will be parts of the new object wave that are not similar to the original, the intensity of the reconstructed wave will be less. It seems logical that the intensity of the reconstructed spot will be a measure of the similarity between these two images, and indeed it can be proven that the spot will measure the exact cross-correlation function between the unstressed and stressed reflectance versus spatial coordinates (refs. 200, 201, 208 and 209).

Holographic Image Deblurring and Spatial Filtering

Another very important optical processing function operation that can be carried out is called the convolution operation or the spatial frequency filtering process. Image deblurring is the inverse of a convolution operation.

*Now with Radiation, Inc., Electro-Optics Center.

**There are special cases when these generalizations are not correct (ref. 207).

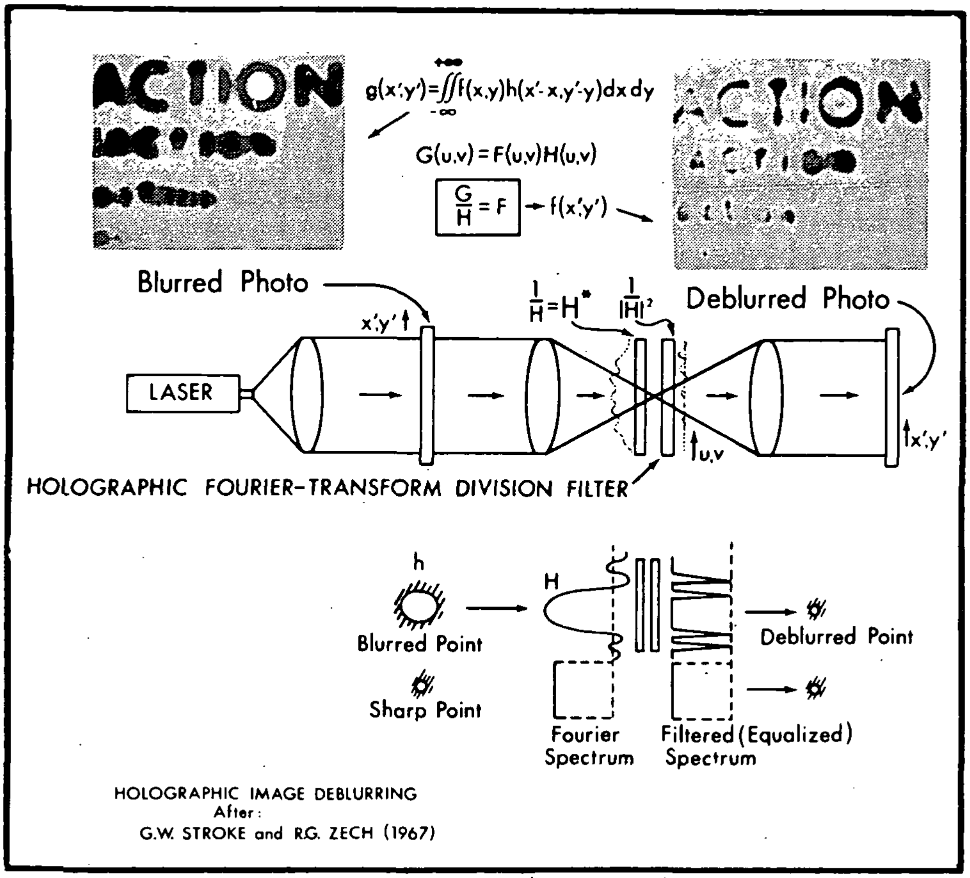


FIGURE 83.–Holographic image deblurring.

The best description of a convolution process is a superposition or a process of repeated addition. An ordinary optical lens performs a convolution when forming an image of an object. In this case, the blur function of a lens is the shape and amplitude of the distorted image formed by the lens of a perfect point source object, due to the aberrations or imperfections of the lens. The image formed by a lens of any object will merely be the superposition on the image plane of all its blur functions represented by the points in the object.

Another more familiar way to think about the action of the lens on the object is to consider the lens as modifying the component spatial frequency of the object, both in amplitude and phase, by some type of transform relationship. Figure 83 is a diagram that illustrates the deblurring process. It is similar to the setup of figure 82 except that the optical path can be straightened out and simplified because the object is a graphic transparency. Note that the transform division takes place in the Fourier or spatial frequency plane, u, v. Because of practical considerations the operation is performed by two filters which successively multiply by H^* and $1/H^2$. The result is multiplication by $1/H\ (u,\ v)$, the reciprocal of the blurring function transform, $H\ (u,\ v)$, and hence a cancellation of the blurring effect. After the multiplication operation, the final lens transforms the resultant image back into the space or image plane x^1, y^1. The blurred image on the left was sharpened to the image on the right by this process (refs. 209 through 211).

Glossary

Aberrations (of image)—Distortions in shape, color, focus, and density of images caused by imperfect optical elements (i.e., lens, prism, mirror, screen, etc.). Types such as coma, astigmatism, field curvature, distortion, and chromatic and spherical aberrations.

Amplitude (of wave)—A measure of the maximum displacement of the wave crest from its undisturbed position (or the maximum electric or magnetic field strength of an electromagnetic wave).

Beam (of energy)—The locus of all series of wavefronts projected from the source and directed toward given objects or positions in space.

Beam splitter—A device to produce two separate beams from one incident beam. This can be done with prisms or halfsilvered mirrors.

Brightness (of image)—A measure of the rate of luminous energy reflected or radiated from a small area of a source, or from a joint source into a small directional region (or solid angle).

Coherence length—The maximum tolerable optical path length difference between two energy beams which are forming an interference pattern. This will vary with the degree of spectral purity of the source producing the beams. For example a perfect monochromatic source would have an infinite coherence length.

Coherent (addition)—The vector addition of both the amplitude and phases of different waves of the same frequency at a given time or at a given position.

Coherent (source)—A source radiating coherent waves.

Coherent (waves)—Waves whose frequencies are equal and whose phases are related to each other at a given time or at a given place in space. Coherence can be of two types, temporal and spatial (ch. 2).

Computer-generated holograms—A hologram made synthetically and based on computer calculations of amplitude and/or phase.

Contrast of fringes—The relative difference between the brightness or density of successive bright and dark fringes on a hologram or interferogram.

Crossed polarizer—A dual polarization filter and transducer which transforms varying orientations of polarized waves into an amplitude output.

CW laser—Continuous wave laser—a laser that radiates its energy in an uninterpreted beam.

Density (of film)—The logarithm of the reciprocal of the optical transmission of the film.

Diffraction fanning—The fanning out of a light or energy beam as it pours through a very narrow aperture (opening).

Diffraction efficiency—Ratio of energy projected into the reconstructed image to the energy illuminating the hologram.

Diffraction grating—A mask or special aperture used to break up a white light beam or composite energy beam into its various spectral components through the mechanism of diffraction.

Diffuse reflection—Scattering at all angles from the point of reflection.

Double pass transmittance hologram—A hologram whose object wave was transmitted through the transparent object media to a mirror, reflected back through again, and recorded on the plate.

Emulsion—The coating on a film or plate which is sensitive to the light illuminating it.

Far field (diffraction pattern)—Diffraction pattern produced at a large range from an object which is identical to that which would be produced at an infinite range from the object. This is also called a Fraunhofer diffraction pattern.

f/n or f number (of optics)—The ratio of effective focal length to lens diameter.

Fourier transform plane—Same as spatial frequency plane.

Frequency (of waves)—Number of like phase (peaks, troughs) wavefronts passing a given point in a unit of time.

Fringe—The locus of maximum constructive inter-

ference (light fringe) or destructive interference regions in a space where two or more coherent waves intersect. Fringes can be in two or three dimensions.

Fringe control–Methods of adjusting the position and/or characteristics of the fringe pattern of a holographic interferogram.

Half-wave plate–An electro-optical material used to rotate the plane of polarization of a light beam.

Holocamera–A device for recording or forming a hologram of an object or subject.

Hologram–A recording or picture of a three-dimensional wavefront.

Holographic–Pertaining to or using the principles of holography. For example, holographic equipment uses the principles of holography for its operation.

Holographic matched filter–A particular type of hologram which when illuminated by the type wave it is matched to will transmit a pure plane wave. This plane wave is usually focused into a correlation spot.

Holography–A recording and viewing process which allows reconstruction of three-dimensional images of diffuse objects.

Image redundancy–Multiple storage of the same image.

Incoherent holography–Holograms produced initially from conventional photographs or incoherent optical equipment.

Index of refraction (of a substance)–Ratio of velocity of a wave in a vacuum to its velocity in the substance.

Information content–Containing or transmitting data involving new knowledge. When applied to waves or wavefronts, it includes both amplitude and phase of all parts of a wavefront at a given instant of time.

Inline holography–Hologram produced by single reference beam interferences with waves diffracted or scattered from a small object.

Interference (of waves)–The coherent addition or subtraction of two different wavefronts, which usually forms a third wave different from the first two.

Interference hologram–A holographic interferogram produced by the superposition of two or more hologram exposures.

Interference pattern–The pattern of light and dark fringes produced when two or more coherent waves interfere or intersect.

Interferogram–The record of an interference pattern produced by holography or by conventional optical interference techniques.

Interferometry (holographic)–The process of measuring very small movements or deformations by recording or observing interference wave patterns (either light, electronic, or acoustic).

Irradiance–A measure of the rate of energy falling on a given area.

Laser–Light Amplification by Stimulated Emission of Radiation.

Liquid-surface holography–A form of acoustic holography in which the surface of the water containing the object becomes the hologram record.

Longitudinal wave energy–Waves whose amplitude displacement is in the same or opposite direction as the motion.

Luminous (energy)–Energy whose wavelength is such that the eye is sensitive to it.

Microholograms–Holograms whose image scale is orders of magnitude smaller than microfiche images.

Moire patterns–Pattern resulting from interference beats between two sets of periodic structures in an image.

Monochromatic (source)–All source radiation is exactly of the same wavelength. This is never achieved in practice even with a laser, so the term "quasi-monochromatic" is used to mean nearly of the same wavelength for all practical purposes.

Object wave–The scattered or reflected wave from the object which it is desired to image or "reconstruct."

Optical beam steering–The pointing of an optical beam in various directions by various reflection, refraction, focusing, and diffraction techniques.

Optical correlation–Process of determining the similarity of an optical signal or wave form to a reference-stored signal or wave form. The reference is usually stored as a matched filter.

Optical path length–The total phase change between the source and a given position in the energy beam as measured along the direction of travel of the beam or wavefronts.

Order (of a bright fringe)–Proportional to the path difference between the two wave components producing a fringe (measured in integral numbers of wavelengths). No path difference produces zero order fringes.

Order (of a dark fringe)–Proportional to the path

difference between the two wave components producing a fringe (measured as one-half the quantity of integral half wavelengths less one; i.e., path difference of 3.2 a wavelength produces a 1st order dark fringe).

Period (of wave)—The reciprocal of the frequency of a wave.

Phase (of wave)—The distance between the position of an amplitude crest of a wave train and a reference position measured in units of wavelength, degrees, or radians (one wavelength equals 360°, or 2π radians).

Phase hologram—A hologram in which the fringes recorded in the material will modulate only the phase of the reconstructing energy beam and not the amplitude.

Photopolymers—Polymers which when exposed to light exhibit permanent changes in their transmission or index of refraction.

Plane (wave)—A train of waves whose wavefronts are flat planes traveling in a direction perpendicular to the wavefronts.

Pseudoscopic image—A reversed contour or inside-out image.

Pulsed laser—A laser that radiates its energy during short bursts of times (pulses) and then is inactive until the next burst or pulse. The frequency of these pulses is called the pulse repetition frequency (PRF) of the laser.

Quasi-monochromatic—Nearly of the same wavelength (see monochromatic).

X-rays (of a beam)—Directions of travel of wave energy perpendicular to the series of wavefronts comprising an energy beam.

Real image—Image formed by converging rays which form a focused image in space.

Real-time holographic interferometry—A holographic interferogram made by illuminating with a cw laser the superposition of a hologram of the subject and the live dynamic subject simultaneously. The movement of the subject can then be observed in real time by the formed interference pattern.

Reconstructed image—The image which appears when a hologram is illuminated with the proper light source (usually a laser beam).

Refraction—The bending of a light or energy wave as it passes through material with varying wave velocities or indexes of refraction.

Resolution (of film)—Capacity of film to record fringe lines per unit length.

Rochon prism—A birefringent electro-optical crystal which divides incident unpolarized optical beam into two polarized components.

Scattered (light)—Reflection of light from a surface in all directions in a nonuniform manner.

Scatter plate—A special type of diffusing screen used in producing holographic images with minimum loss of resolution.

Schlieren (photography)—A picture or image in which density gradients in a volume of flow are made visible. The image is produced by refraction and scattering from regions of changing refractive index.

Shadowgraph—A picture or image in which steep density gradients in the glow about a body are made visible, the body itself being presented in silhouette. The image is produced by the second derivative of the refractive index.

Sideband holography—Hologram produced by separate object and reference beams offset at an angle to each other.

Spatial frequency plane—The focusing plane of an optical lens or system where the image represents the spatial Fourier transform of the object spatial function.

Speckle (of laser image)—A particular noise generated by coherent optical systems which causes the image to scintillate in intensity.

Specular reflection—Mirror scattering at one angle from the point of reflection.

Stereoscopic image—An image which appears as a three-dimensional object located in space.

Stored beam hologram—The name given to the preexposed hologram of the subject used in real-time holographic interferometry.

"Synthetic aperture" sidelooking radar—A sidelooking radar that generates very high resolution data by integrating its return signals during the time that the physical aircraft antenna or aperture is traveling through a large distance (making up the synthetic aperture).

Thick hologram—A volume hologram.

Time-averaging interferometry—Pattern produced when a long (much longer than period of waves) time exposure is made of the interference fringes.

Time-differential holographic interferometry—A holographic interferogram made by making two or more sequential flash holographic exposures of the object on a hologram plate. These exposures are usually made with short pulsed laser illumination.

Transducer (acoustic)–A device to convert electrical oscillatory input energy into mechanical acoustical wave energy.

Transverse electromagnetic energy–Waves whose electric field and magnetic field displacements are at right angles to each other and to the direction of propagation (motion) of the wave.

Ultrasound camera–A camera that converts a sound pressure "acoustic image" into an electrical TV-like image by means of the piezo-electric effect.

Uncorrected lenses–Lenses whose image aberrations are quite severe.

Virtual image–Image formed by diverging rays which do not form a focused image in space.

Volume hologram–A hologram with a wave-sensitive volume thick enough to record the three-dimensional fringe patterns to many wavelengths depth.

Wavefront–Surface whose points in an energy beam are all of equal phase or optical path length.

Wavefront reconstruction–An alternate name for holography which indicates that the process re-forms the original wavefront used to form the hologram at a different time and position.

Wavelength–Distance between successive wavefronts of like phase (i.e., from peak to peak, or trough to trough).

Zone plate–The hologram of a point (app. A), also used as a substitute for a lens.

References

1. Gabor, D.: A New Microscopic Principle. Nature, vol. 161, 1948, p. 777.
2. Leith, E. N.; and Upatnicks, J.: Wave Front Reconstruction With Continuous Tone Objects. JOSA, vol. 53, no. 12, Dec. 1963, p. 1377.
3. Caulfield, H. J.; and Lu, S.: Applications of Computer Generated Holograms. The Applications of Holography. Wiley-Interscience, 1970, ch. 10.
4. Jeong, T. H.; and Wender, D. C.: What Future Holography. Optical Spectra, Jan. 1972, p. 24.
5. Data obtained at a Technology Utilization Conf. during a visit to TRW Systems Group, Redondo Beach, Calif.
6. Lehmann, M.: Holography Technique and Practice. The Engineering Uses of Holography. Cambridge Univ. Press, 1970, pp. 1-4.
7. Leith, E. N.; and Upatnicks, J.: Wavefront Reconstruction With Continuous-Tone Objects. JOSA, vol. 53, no. 12, Dec. 1963, p. 1377.
8. Shulman, A. R.: Optical Data Processing. John Wiley & Sons, Inc., 1970, pp. 64-71.
9. Kock, W. E.: Fundamentals of Holography. Laser Focus, Feb. 1969, p. 26.
10. Jenkins, F.; and White, H.: Fundamentals of Optics. McGraw-Hill, 1950, pp. 353-358.
11. Collier, R.; Burckhardt, C.; and Lin, L.: Optical Holography. Academic Press, 1971, p. 64.
12. Shulman, A. R.: Optical Data Processing. John Wiley & Sons, Inc., 1970, pp. 503-509.
13. Collier, R.: Optical Holography. Academic Press, 1971, p. 78.
14. Collier, R.: Optical Holography. Academic Press, 1971, pp. 139-152.
15. Shulman, A. R.: Optical Data Processing. John Wiley & Sons, Inc., 1970, pp. 514-515.
16. Collier, R.: Optical Holography. Academic Press, 1971, pp. 272-280.
17. Caulfield, H. J.; and Lu, S.: Applications of Holography. Wiley-Interscience, 1970, p. 33.
18. Collier, R.: Optical Holography. Academic Press, 1971, pp. 204, 220.
19. Robinson, D. M.: Interim Tests on a Holographic Technique for Photographing High-Speed Mil-Size Particles. Holographic Instrumentation Applications. NASA SP-248, 1970, pp. 221-235.
20. Robinson, D. M.: Magnification in Far-Field Holography. LWP No. 684, Dec. 3, 1968.
21. Collier, R.; Burckhardt, C.; and Lin, L.: Optical Holography. Academic Press, 1971, pp. 47-52.
22. Robinson, D. M.: A Theoretical Calculation of Edge "Smear" in Far-Field Holography Using a Short-Cut Edge Trace Technique. LWP No. 781, Aug. 7, 1969.
23. Robinson, D. M.: Holography of Static and Dynamic Microsize Objects. LWP No. 503, Oct. 30, 1967.
24. Wuerker, R. F.; et al.: Producing Holograms of Reacting Sprays in Liquid Propellant Rocket Engine. TRW Systems Group Final Report, July 31, 1968.
25. Wuerker, R. F.; et al.: Producing Holograms of Reacting Sprays in Liquid Propellant Rocket Engines, Phase II. TRW Systems Group Interim Report, May 24, 1968.
26. Wuerker, R. F.; and Heflinger, L. O.: Pulsed Laser Holography. The Engineering Uses of Holography. Cambridge Univ. Press, pp. 99-114.
27. Clayton, R. M.; and Wuerker, R. F.: Applying Holography to Reacting Spray Studies. Holographic Instrumentation Applications. NASA SP-248, 1970, pp. 117-128.
28. Wuerker, R. F.; et al.: Analysis of Holograms of Reacting Sprays. TRW Final Report No. 12299-6001-RO-00, Jan. 1970.
29. Ward, J. H.: Feasibility Study of Velocity Synchronized Fourier Transform Hologram Camera System. Tech. Operations, Inc., Report No. CR-86147, Apr. 1969.
30. Dotson, W. P.: The Effect of Object Motion in Fraunhofer Holography With Application to Velocity Measurements. NASA TN D-5515, Dec. 1969.
31. Kurtz, R. L.; et al.: A Holographic Technique for Recording a Hypervelocity Projectile With Front Surface Resolution. AO, vol. 9, no. 7, July 1970, p. 1040.
32. Kurtz, R. L.: A Holographic System that Records Front-Surface Detail of a Scene Moving at High Velocity. Ph.D. Thesis, Va. Polytech. Inst., June 1971.
33. Kurtz, R. L.: Hybrid Holographic System Using Reflected and Transmitted Object Beams Simultaneously. Patent No. 3 535 014, Oct. 1970.
34. Lackner, H. G.: Method and Apparatus for Checking the Stability of a Setup for Making Reflection-Type Holograms. Invention Disclosure, June 1971.
35. NASA Tech Brief: Variable Ratio Beam Splitter for Laser Applications. ARC Brief 71-10265, Aug. 1971.
36. Spencer, R. C.: A Survey of Holographic Techniques and Applications to Aerospace Research. LWP No. 734, Mar. 27, 1969.
37. Shulman, A. R.: Optical Data Processing. John Wiley & Sons, Inc., 1970.
38. International Holographics, Inc., Flier.
39. Korad Holographic News Letter No. 2., Dec. 1970.
40. Laser Tech Flier.
41. Jordon Engineering Associates, Inc., Fliers.
42. GCO, Inc., Fliers.
43. Gartner Scientific Corp. Flier.
44. Holobeam Flier.

45. Matthews, B. J.: Measurement of Fine Particulate in Pollution Control. SPIE, Developments in Holography, 1971, pp. 157-170.
46. Technology Utilization Survey Conf. at TRW Systems Group.
47. Belz, R. A.; and Dougherty, N. S.: Holography of Reacting Liquid Sprays. ARO Internal Memo, Aug. 5, 1971.
48. Trolinger, J. D.: Review of Holographic Instrumentation at Arnold Engineering Development Center. Conf. on Holography and Optical Filtering, Huntsville, Ala., May 1971.
49. Trolinger, J. D.; and Gee, T. H.: Resolution Factors in Edgeline Holography. AO, vol. 10, June 1971, p. 1319.
50. The Laser Weekly, June 21, 1971; Aug. 24, 1970; May 19, 1970; Apr. 15, 1968.
51. McCreekerd, J. T.; et al.: Holography and Stereoscopy. CIT Quantum Electronics Symposium, AD 688895, May 1969.
52. Bobin, J. L.; et al.: Density Profile Determination in a Laser Created Plasma by a Holographic Method. Commissariat Energie Atomique, N70-20775, 1969.
53. Raterink, H. J.; et al.: Determination of the Bubble Spectrum in a Cavity Tunnel With the Help of Holography. Techniseh Physische Diemt, N71-14271, June 30, 1970.
54. Sherman, G. C.: Wavefront Reconstruction and Its Application to the Study of the Optical Properties of Atmospheric Aerosols. Aerospace Corp. Report No. ATR-69 (8103)-1, July 31, 1969.
55. Hickling, R.: Holography of Liquid Droplets. General Motors Research Report No. GMR 869, Apr. 10, 1969.
56. Shafner, F. M.; et al.: Fundamentals of Holographic Velocimetry. Tenn. Univ. Space Inst. Report No. AFFOL-TR-68, AD 692477, Nov. 1968.
57. Lasersphere, Aug. 23, 1971.
58. Holography is Applied Anew to Photographing the Stars. Laser Focus, May 1969, pp. 16-18.
59. Erickson, K. E.: Holographic Method of Monitoring the Performance of a Large Telescope Mirror. NASA SP-233, Optical Telescope Technology, 1970.
60. Holographic Art Studio Built on a Base of Sand. Laser Focus, Feb. 1970.
61. Leith, E. N.: Optical Processing Techniques. Final Report CR-97741, Oct. 1968.
62. Leith, E. N.: Optical Processing Techniques. Status Report CR-92712, Dec. 1967.
63. Close, D. H.; et al.: Hologram Recording on Photopolymer Materials. Applied Physics Letters, March 1, 1969, p. 159.
64. Holography in Unconventional Materials. Optical Spectra, Nov. 1970, pp. 26-30.
65. Thin-Film Holograms Feature Instant Readout. Electro-Optical Systems Design, Dec. 1971, p. 8.
66. Shofner, F. M.: Infrared In-Line Holography. Proc. E-O Systems Design Conf., 1971 East, Sept. 1971, p. 286.
67. Cluvian, J. S.; et al.: Infrared Holography at 10.6 Microns. Applied Physics Letters, vol. 15, no. 4, Aug. 15, 1969, pp. 123-125.
68. Izawa, T.; et al.: Infrared Holography With Organic Photochromic Films. Applied Physics Letters, Univ. of Tokyo, vol. 15, no. 7, Oct. 1, 1969, pp. 201-203.
69. Kobayashi, S.; et al.: IR Interferometry Using Liquid Crystals and Their Applications. Proc. E-O Systems Design Conf., 1971 East, Sept. 1971, p. 280.
70. Optical Processing Techniques. Univ. of Mich. Semi-Annual Report, NASA CR-92712, Dec. 1967.
71. Technology Utilization Conf., Univ. of Mich., Sept. 1971.
72. System for Rapidly Producing Multicolor Maps for Holographic Display. The Laser Weekly, June 28, 1971, pp. 7-8.
73. Holographic Method for Viewing Changes in a Scene. SPIE Journal, vol. 9, no. 2, Patent No. 3 541 252, Dec.-Jan. 1971.
74. Technology Utilization Conf., MSC, Houston, Aug. 1971.
75. Rosen, L.: Recording and Reconstructing Focused Image Holograms. Patent No. 3 535 012, Oct. 20, 1970.
76. Rosen, L.: Focused Image Holography With Extended Sources. Patent No. 3 535 013, Oct. 20, 1970.
77. How Fisher Body's New Integrated Holographic Display Works. Laser Focus, vol. 4, no. 21, Nov. 1968, pp. 26-28.
78. Conductron Exhibits Large Hologram. The Laser Weekly, vol. 1, no. 18, Jan. 22, 1968, p. 6.
79. Hologram Viewer Portable. The Laser Weekly, vol. 2, no. 4, Oct. 14, 1968, p. 5.
80. New Products–A Low-Cost Camera/Viewer That Makes and Displays Holograms. The Laser Weekly, Apr. 6, 1970, p. 3.
81. New Products–Compact, Attache-Case Viewer for Viewing Holograms. The Laser Weekly, Mar. 24, 1969, p. 5.
82. Twin Japanese Lasers Produce 3-Color Holograms. Laser Focus, vol. 5, Jan. 1969, pp. 13-14.
83. Low-Price Holographic Camera Introduced. The Laser Weekly, vol. 2, no. 1, Sept. 23, 1968, p. 2.
84. System H-9000 Holoscan. Optronics International, Inc. (company brochure).
85. Stereo and Color Displays With Holography are Described to OSA by Radiation, Inc. Laser Focus, vol. 7, no. 5, May 1971, pp. 17-19.
86. Friesem, A. A.; et al.: Holographic Application in High Density Document Storage and Retrieval. Presented at the 15th Annual SPIE Technical Symposium, Sept. 1970.
87. Holographic Displays in Real Time Move From Dream to Development. Electronic Design, July 22, 1971.
88. Mueller, R. K.; et al.: A Real Time Holographic 3-D Display. Presented at Electro-Optics 1971 Conf., New York City, Sept. 1971.
89. Holography May Aid Pilots. The Laser Weekly, vol. 1, no. 37, June 3, 1968, pp. 4-5.
90. Harris, T. J.; et al.: Holographic Head-Up Display. IBM Final Report, AD 703683, Mar. 1970.
91. Gabor, D.; Kock, W. E.; and Stroke, G. W.: Holography. Science, vol. 173, no. 3991, July 2, 1971.

92. Color TV Tapes for Home May Form First Mass Market for Holography. Laser Focus, Oct. 1969.
93. Cox, Mary E.: Closeup of Holographic Microscopy. Laser Focus, Feb. 1971, p. 41.
94. Collier, R. J.; et al.: Optical Holography. Academic Press, 1971, p. 360.
95. Leith, E. N.; and Upatnicks, J.: Microscopy by Wave Front Reconstruction. JOSA, vol. 55, 1965, p. 569.
96. van Ligten, R. F.; et al.: Nature, vol. 211, 1966, p. 282.
97. van Ligten, R. F.: Holographic Microscopy for the Determination of Failure Mechanisms in Monolithic Circuits. NASA CR-1394, July 1969.
98. Close, D. H.: Lunar Surface Holography Experiment Instrument Feasibility Demonstration. Hughes Aircraft Co., NASW-2092, Final Report, Dec. 1970.
99. Introducing the AO Holographic Microscopy (brochure of AO).
100. Caulfield, H. J.; and Lu, S.: The Applications of Holography. Wiley-Interscience, 1970, p. 125.
101. Holographic Microscopy Helps the Navy Study "The Bends." Laser Focus, Apr. 1969, p. 29.
102. Caulfield, H. J.; and Lu, S.: The Applications of Holography. Wiley-Interscience, 1970, pp. 81-85.
103. Miller, C. G.; and Stephens, J. B.: Flash Holography Applied to Fluid Heat-Transfer Phenomena. NASA SP-248, Jan. 1970 p. 205.
104. Technology Utilization Conf. with TRW Systems Group, Aug. 1971.
105. Brooks, R. E.; and Heflinger, L. O.: Holographic Instrumentation Studies. TRW Final Report on Contract No. NAS-2-4992, Dec. 1970.
106. Brooks, R. E.; and Heflinger, L. O.: Holographic Instrumentation Studies. NASA SP-248, 1970, p. 57.
107. Multi-Frequency Lasers for Holographic Contouring. Invention Abstract, NASA Case No. ARC-10341-1.
108. Multi-Frequency Laser Beams for Holographic Contouring. NASA Tech Brief 71-10534.
109. Long Range Holographic Contour Mapping Concept. NASA Tech Brief 69-10700.
110. Badin, R.; and Chen, J. C.: Holographic Interferometry Application to Shell Structures. JPL Space Programs Summary 37-64, vol. III, p. 101.
111. Holographic Interferometry Application to Shell Structures. Conf. on Holography and Optical Filtering, Huntsville, Ala., May 24, 1971.
112. Aprahamian, R.; and Evensen, D. A.: Applications of Holography to Vibrations, Transient Response, and Wave Propagation. NASA CR-1671.
113. Aprahamian, R.; and Evensen, D. A.: Applications of Holography to Applied Mechanics. NASA SP-248, Jan. 1970, p. 89.
114. Vibration Testing and Analysis Using Holography. NASA Tech Brief 71-10352.
115. Vibration Analysis by Time-Average Holography. NASA Tech Brief 71-10333.
116. Aprahamian, R.; and Evensen, D. A.: Applications of Holography to Wave Propagation in Shells and Vibrations at High Temperature. Conf. on Holography and Optical Filtering, Huntsville, Ala., May 24, 1971.
117. Evensen, D. A.: Holographic Measurement of Wave Propagation in Axialsymmetric Structures. TRW Final Report No. AM-71-8, Nov. 16, 1971.
118. Howlett, J. T.; and Raney, J. P.: A Model Solution for Wave Propagation in Finite Shells of Revolution. AIAA/ASME 11th Structures, Structural Dynamics, and Materials Conf., Apr. 1970.
119. Brown, R. M.: Fringe Stabilization for Holography. NASA SP-248, Jan. 1970, p. 197.
120. Technology Utilization Conf., ARC, Aug. 1971.
121. Hubbard, P. A.; and Jacobson, C. F.: Holographic Techniques for the Analysis of Steady State and Transient Vibrations. NASA SP-248, Jan. 1970, p. 41.
122. Vibration, Flutter, and Transient Analysis of Using Holographic Methods. Final Report of GCO, Inc., on Contract NAS-8-21369, June 1970.
123. Spencer, R. C.; et al.: Real-Time Flow Visualization Using Holographic Moire Patterns. LWP No. 567, Feb. 1968.
124. Goad, J. H.: Review of Holographic Instrumentation at LRC. NASA SP-248, Jan. 1970, p. 33.
125. Finite Fringe Hologram. NASA Tech Brief 70-10271.
126. Brown, R. M.: A Holographic Flow Visualization System. NASA SP-248, p. 213.
127. Williams, J. R.: Nondestructive Testing by Holographic Interferometry (to be published). Physik in Unserer Zeit, 1972.
128. Williams, J. R.: Nondestructive Testing by Holographic Interferometry. NASA SP-248, Jan. 1970, p. 161.
129. Williams, J. R.: Holographic Analysis of Contaminant Deposits on Optical Surfaces. 17th International ISA Aerospace Instrumentation Symposium, Las Vegas, May 1971.
130. Two-Color Holography. NASA Tech Brief 69-10662.
131. Technology Utilization Survey Conf., NASA-MSFC, July 1971.
132. Aas, H. G.; et al.: Investigation to Determine the Feasibility of Employing Laser Beam Holography for the Detection and Characterization of Bond Defects in Composite Material Structures. UARL Final Report on Contract No. NAS-1-9926, Feb. 1971.
133. Sweeney, D. W.; and Vest, C. M.: Applications of Holographic Interferometry to Nondestructive Testing. Univ. of Mich.
134. Meer, E.; et al.: Vibration and Deformation Measurements Using Holography Techniques. JPL Space Program Summary 37-61, vol. III, p. 187.
135. Norden, B. N.; and Williams, J. R.: Analysis of Optical Component Movement by Holographic Interferometry. NASA TM-X-2227, Mar. 1971.
136. Michalak, M. W.: Report on Holographic Interferometry Theory and Experiment, May 28, 1970.
137. Howell, B. J.: Holographic Interferometry as a Means of Measuring Small Linear and Angular Displacements. NASA SP-248, p. 147.
138. Technology Utilization Survey Conf., Univ. of Mich., Sept. 1971.
139. Brooks, R. E.; and Heflinger, L. O.: Holographic Instrumentation Studies. TRW Report No. 12122-6007-RO-00, app. A, Dec. 1970.

140. Fine Line Sensitivity for Holographic Interferograms. NASA Tech Brief 69-10663.
141. Ballard, G. S.; and Testerman, M. K.: Instrumental Holographic Techniques. NASA SP-248, p. 103.
142. Testerman, M. K.: Investigation of Laser Properties Relevant to the Measurement of Physical Parameters. Report on Contract NGL-04-001-007, June 1, 1970.
143. GCO Mark Series, Industrial Analyzers. GCO, Inc.
144. Holography a New Dimension. Rohr Corp., Oct. 1970.
145. GCO PT-12 Holographic Tire Analyzer. GCO, Inc., Aug. 1970.
146. Holograms Pinpoint Flaws in New Automobile Tires. Laser Focus, Jan. 1969.
147. Way, F. C.; et al.: Holographic Techniques Applied to the Solution of Aerospace Problems. Conf. on Holography and Optical Filtering, Huntsville, Ala., May 1971.
148. van Hees, W.: An Application of Holographic Interferometry to the Study of Transient Phenomena of Rolling-Contact Bearings. NSR & DC, AD 864265, Jan. 1970 (UNCL, Ltd.).
149. Jeffers, L. A.: Investigation of a Diaphragm-Type Pressure Transducer Using Holographic Interferometry. Proc. E-O Systems Design Conf., 1969.
150. Trolinger, J. D.: Review of Holographic Instrumentation at Arnold Engineering Development Center. Conf. on Holography and Optical Filtering, Huntsville, Ala., May 1971.
151. Technology Utilization Survey Conf., Univ. of Mich., Sept. 1971.
152. Kersch, L. A.: Advanced Concepts of Holographic Nondestructive Testing. National Spring Conf. of the American Society for Nondestructive Testing, Mar. 1971.
153. Sweeney, D. W.; and Vest, C. M.; et al.: Holographic Detection of Microcracks. Journal of Basic Engineering, June 1971, p. 237.
154. Aleksoff, C. C.: Temporally Modulated Holography. Applied Optics, vol. 10, no. 6, June 1971, p. 1329.
155. Haines, K.; and Brum, D.: Proc. IEEE, vol. 55, 1967, p. 1512.
156. Optical Processing Techniques. Final Report CR-97741, Univ. of Mich., Oct. 1968.
157. Jacobson, A. D.; Evtuhov, V.; and Neeland, J. K.: Motion Picture Holography. Applied Physics Letters, vol. 1A, no. 4, Feb. 15, 1969, pp. 120-122.
158. Kurtz, R. L.: Multiple Image Storing System for High Speed Projectile Holography. NASA Case MFS-20596, Feb. 1970.
159. Carpluk, G. T.: Stereo Laser Framing Camera. Calif. Univ., Livermore, Lawrence Radiation Lab., June 29, 1970.
160. Smigielski, P.: Holography of Moving Objects. Application to the Study of Phased Objects. Institut Franco-Allemand de Recherches, Mar. 11, 1968.
161. Zaidel, A. N.: Holography and Cine-Holography of Rapidly Occurring Processes. (NASA TT-F-12641), Techtron Corp., 1969.
162. Scientist Patents Holographic 3-D Movies. SPIE Journal, vol. 8, no. 3, Feb.-Mar. 1970, p. G-22.
163. Germans Negotiate for Rights to Gabor's Holographic Movies. Laser Focus, vol. 6, no. 1, Jan. 1970, p. 18.
164. Gabor, D.; Kock, W. E.; and Stroke, G. W.: Holography. Science, vol. 173, no. 3991, July 2, 1971, pp. 11-23.
165. Philip's Holographic Movie "Studio" Begins Filming With Reflected Light. Laser Focus, vol. 6, no. 4, Apr. 1970, pp. 18-20.
166. Holographic 3D Movie. The Laser Weekly, vol. 2, no. 4, Oct. 14, 1968, p. 3.
167. deBitello, D. J.: Horizontal Strip Technique Reduces BW Needed for Holographic Data Trans. Non NASA (Pat.) Philips Labs., Mar. 1968.
168. Lessing, L.: Getting the Whole Picture From Holography. Fortune, vol. LXXXIV, no. 3, Sept. 1971, pp. 110-114 and 144-146.
169. Berrang, J. E.: Television Transmission of Holograms Using a Narrow-Band Video Signal. The Bell System Technical Journal, vol. 49, no. 5, May-June 1970, pp. 879-887.
170. Holography Phone Use Seen. The Laser Weekly, vol. 1, no. 41, July 1, 1968, p. 2.
171. New Developments–Lensless, Three-Dimensional, Laser-Beam Photography. The Laser Weekly, Sept. 7, 1970, p. 4.
172. Mueller, R. K.: Acoustic Holography. Proc. IEEE, vol. 59, no. 9, Sept. 1971, p. 1327.
173. Cribbs, R. W.: Optical Processing of Microwave Signals for Non-Destructive Testing. NASA SP-248, p. 129.
174. Investigation Into the Resolution of Defects by Microwave Holography. Electro-Physics Interim Report NAS 7-759, Mar. 1970.
175. Larson, R. W.; et al.: Microwave Holography. Proc. IEEE, vol. 57, Dec. 1969, p. 2162.
176. Iizuka, K.: A Method for Photographing Microwaves with a Polaroid Film. Interim Report NASA CR-94305, NASA NGR 22-007-056, Mar. 1968.
177. Iizuka, K.: Microwave Holography by Means of Optical Interference Holography. Applied Physics Letters, vol. 17, no. 3, Aug. 1970, pp. 99-101.
178. Microwave Holography Maps Surface Expansion. Microwaves, vol. 9, no. 11, Nov. 1970, p. 26.
179. Metherell, A. F.; et al.: A Study on Range Gated Temporal Reference Acoustical Holography. McDonnell-Douglas NASA CR-112412, July 1970.
180. Aprahamian, R.; and Bhuta, P. G.: NDT by Acousto-Optical Imaging. Conf. of American Society for Non-Destructive Testing, Oct. 19-22, 1970.
181. Aprahamian, R.: Non-Destructive Testing Acousto-Optical Imaging. TRW Final Report, Oct. 1970.
182. Singh, J. J.: Acoustic Holography–Problems Associated With Construction and Reconstruction Techniques. LWP No. 824, Nov. 1969.
183. Technology Utilization Survey Conf. Call.
184. Pfeifer, J. L.; et al.: Holograms for Acoustic Wave Reconstruction. Bendix Research Lab. Paper.
185. Leith, E. N.: Quasi-Holographic Techniques in the Microwave Region. Proc. IEEE, vol. 59, no. 9, Sept. 1971, p. 1305.

186. Microwave Imaging Helps FAA Foil Hijackers. Microwaves, vol. 10, no. 8, Aug. 1971, p. 9.
187. The Inside Story, Acoustic Holography. Holosonics Brochure.
188. The Sound of Failure. Industrial Research, Apr. 1971, p. 40.
189. Acoustic Holography: A New Dimension in Seeing with Sound. Machine Design, Sept. 2, 1971, p. 70.
190. Ultrasonic Holography Might Help Detect Breast Cancer in Early Stages. Laser Focus, Oct. 1968, p. 34.
191. Ultrasonic Hologram Detects Soft Tumors. The Laser Weekly, Apr. 15, 1968, p. 4.
192. The Prediction of Sex of an Unborn Child. The Laser Weekly, Jan. 4, 1971, p. 2.
193. Laser and Sound Waves Look into Solid Objects. Microwaves, Mar. 1971.
194. Burcett, O. J.; and Twin, J. L.: Using Laser Holography for Nondestructive Testing. Mechanical Engineering, Mar. 1971.
195. Marom, E.; Mueller, R. K.; et al.: Design and Preliminary Test of an Underwater Viewing System Using Sound Holography. Presented at Third Symposium on Acoustical Holography (Newport Beach, 1970), Feb. 1971.
196. Farrah, H. R.; et al.: An Underwater Viewing System Using Sound Holography. Acoustical Holography, vol. 2, Plenum Press, 1970, p. 173.
197. Goetz, G. G.; et al.: Real-Time Optical Reconstruction and Display of Acoustic Holograms for an Underwater Viewing System. Proc. E-O Systems Design Conf., Sept. 1971, p. 202.
198. Acoustic Microscope. Laser Focus, Sept. 1971. p. 29.
199. Acoustic Microscope Shows New Features of Specimen. Machine Design, vol. 43, no. 21, Sept. 1971, p. 10.
200. Shulman, A. R.: Principles of Optical Data Processing for Engineers. NASA TR R-327, May 1970, p. 70.
201. Jenkins, R. W.: Holographic Optical Data Processing. NASA TM-X-53961, Nov. 1969.
202. Grebowsky, G. J.: Fourier Transform Representation of an Ideal Lens in Coherent Optical Systems. NASA TM-X-63347, Aug. 1968.
203. Strong, J. P.: Onboard Optical Processing. NASA SP-248, 1970, p. 189.
204. Larson, R. K.: Experiments in Spatial Coherent Optical Filtering. NASA X-711-71-292, June 1971.
205. Jenkins, R. W.; et al.: Holographic Analysis of Printed Circuit Boards. Presented at American Society for Nondestructive Testing, Cleveland, Oct. 22, 1970.
206. Jenkins, R. W.: Nondestructive Testing by Optical Cross-Correlation. NASA SP-248, 1970, p. 181.
207. Collier, R. J.; and Burckhardt, C. B.: Optical Holography. Academic Press, 1971, pp. 22-26.
208. Shulman, A. R.: Optical Data Processing. John Wiley & Sons, Inc., 1970, p. 334.
209. Goodman, J. W.: Spatial Filtering and Applied Information Processing. Introduction to Fourier Optics. McGraw-Hill, 1968, ch. 7.
210. Stroke, G. W.: Holographic Image Deblurring. Optical Spectra, Nov. 1970.
211. Stroke, G. W.: Holographic Image Deblurring Methods. Developments in Holography. SPIE Seminar, Apr. 14-15, 1971.
212. Noise Diffraction Patterns Eliminated in Coherent Optical Systems. NASA Tech Brief 71-10236.
213. Grebowsky, G. J.; Shulman, A. R.; et al.: Elimination of Coherent Noise in a Coherent Light Imaging System. NASA X-521-70-76, Mar. 1970.
214. Bardos, A.: Investigation of 10^{10} Bit Optical Memory. Carson Labs., Inc., Interim Report on NAS12-125, Oct. 16, 1967.
215. Investigation of Optical Memory Techniques. Radiation, Inc., Final Report NASA CR-102973, N71-15136, Oct. 1970.
216. Optical Read/Write Memory System Design. Radiation, Inc., Final Report, NASA CR-103058, N71-19775, Feb. 19, 1971.
217. Friesem, A. A.; and Roberts, H. N.: Investigation of Optical Memory Techniques. NASA SP-248, 1970, p. 73.
218. Optical Read/Write Memory System Components. Radiation, Inc., Apr. 30, 1971.
219. Up to 1000 Holograms Stored in One Crystal. Laser Focus, vol. 4, no. 23, Dec. 1968, pp. 15-17.
220. Holography in Data Storage System. The Laser Weekly, vol. 1, no. 34, May 13, 1968, pp. 2-3.
221. Thaxter, J. B.: Electrical Control of Holographic Storage in Strontium-Barium Niobate. Applied Physics Letters, vol. 15, no. 7, Oct. 1, 1969, pp. 210-212.
222. Fe:$LiNbO_3$ Crystals Ideal for Holographic Storage Now Available. Lasersphere, vol. 17, no. 13, Aug. 9, 1971.
223. Keneman, S. A.; et al.: Storage of Holograms in a Ferroelectric-Photoconductor Device. Applied Physics Letters, vol. 17, no. 4, Aug. 15, 1970, pp. 173-175.
224. Duncan, R. C.: Photochromic Materials Research for Optical Display. RCA Final Report, NAS5-10335, May 1971.
225. Lasersphere, vol. 1, no. 19, Nov. 15, 1971.
226. Holographic Mass Memories for Off-Track Betting. RCA Final Report, Sept. 1971, p. 4.
227. Holographic Memory Techniques Described by IBM and Toshiba. Laser Focus, vol. 6, no. 6, June 1970, pp. 16-18.
228. laMacchia, J. T.: Holographic Optical Memories—Promise and Problems. Proc. SPIE, Developments in Holography, Apr. 1971, p. 51.
229. Schaefer, D.; Husain-Abidi, A. S.; et al.: Technology Utilization Survey Conf. at GSFC, Data Techniques Branch.
230. Gibson, J. E.: Biosystems Engineering Research. NASA CR-107927, Oct. 1969, p. 64.
231. Tischer, F. J.: A Study of Optical Data Processing and Reduction. NASA CR-95803, June 1968.
232. Husain-Abidi, A. S.; et al.: Fourier Transformable Properties of Paraboloidal Mirror Segments. NASA X-711-71-156, Mar. 1971.
233. Husain-Abidi, A. S.: On-Board Spacecraft Optical Data Processing. NASA X-711-71-259, June 1971.
234. Hallock, J. N.: Holography and Spacecraft Attitude. Proc. E-O Systems Design Conf., Sept. 1969, p. 380.

235. Welch, J. D.: Image Media Investigation for Holographic Star Field Mapper. NASA CR-86336, Jan. 1970.
236. Development of Optical Data Processing Techniques Applicable to Detection and Study of Meteor Trails. Univ. of Tenn. Space Inst. Final Report on NAS 8-24393, Dec. 1970.
237. Optical Processing Techniques. Mich. Univ. Final Report on NASA CR-97741, Oct. 1968.
238. Hallock, J. N.: A Holographic Image Enhancement Technique. Patent Application ERC-10135, July 1969.
239. Shofner, F. M.; et al.: Selectivity and Noise Rejection Characteristics of Matched Filters. Proc. E-O Systems Design Conf., Sept. 1970, p. 35.
240. Automatic Personnel Verifier. KMS Brochure, 1971.
241. Fool Proof Identification. Optronics Inter., Inc., Brochure.
242. Low Noise Two Lens Optical Correlator. KMS Brochure, 1967.
243. VanderLugt, A.: Optical Processing. Proc. SPIE, Developments in Holography, Apr. 1971, p. 117.
244. VanderLugt, A.: Application of Optical Processing. Paper, Electro-Optics Center, Radiation, Inc.
245. McMahon, D. H.: Holographic Microfilm. Laser Focus, Oct. 1970.
246. Friesen, A. A.; et al.: Holographic Application in High Density Document Storage. Presented at 15th SPIE Technical Symposium, Sept. 1970.
247. Kozma, A.; et al.: Holographic Recording and Retrieval System. Presented at IEEE/OSA Conf. on Laser Engineering and Applications, June 1971.
248. Aleksoff, C. C.: Holographic Analysis and Display of Laser Modes. Applied Optics, vol. 10, 1971, p. 1329.
249. Shofner, F. M.; et al.: Optical Processors for Holographic Velocimetry Data. AD 703299, Feb. 1970.
250. King, M.: Generalized Holographic Recording of Electronic Signals. Proc. E-O Systems Design Conf., Sept. 1969.
251. One Plus One Equal More Than Two. Optical Spectra, Feb. 1971, p. 16.
252. Proposal for an Experiment to Determine the Feasibility of Holographic Assistance to Fingerprint Identification, 1971.
253. Shofner, F. M.: Infrared In-Line Holography. Proc. E-O System Design Conf., 1971 East, Sept. 1971, p. 286.
254. Cluvian, J. S.; et al.: Infrared Holography at 10.6 Microns. Applied Physics Letters, vol. 15, no. 4, Aug. 15, 1969, pp. 123-125.
255. Izawa, T.; et al.: Infrared Holography With Organic Photochromic Films. Applied Physics Letters, Univ. of Tokyo, vol. 15, no. 7, Oct. 1, 1969, pp. 201-203.
256. Kobayashi, S.; et al.: IR Interferometry Using Liquid Crystals and Their Applications. Proc. E-O Systems Design Conf., 1971 East, Sept. 1971, p. 280.
257. Kryzyzkowski, P. F.; and Pucilowski, J. J.: A Technique for Dissecting and Recording Holographic Information. AD-696429, Sept. 1969.
258. Goodman, J. W.; et al.: Techniques for Long-Range Holographic Imaging. AD 843518, Sept. 1968.
259. Goodman, J. W.: An Introduction to the Principles and Applications of Holography. Proc. IEEE, vol. 59, no. 9, Sept. 1971, p. 1292.
260. Hall, William D.; et al.: Real-Time Transducer for Optical Processing. Univ. of Mich. Concept Paper, Aug. 1971.
261. Korad Holographic Newsletter. No. 2, Dec. 1970.
262. News From TRW Instruments.
263. Laboratory Holographic Systems 1303, 1306, 1309 Brochure. GCO, Inc., Apr. 1, 1971.
264. 60-627 Holographic Laboratory. Metrologic Instruments, Inc., Brochure, 1970.
265. Laser Focus 1972 Buyers Guide. Advanced Technology Publications, Inc., Newtonville, Mass., Jan. 1972.
266. Electro-Optical Master Catalog. E-O Systems Design, Milton S. Kever Publications, Inc., July 1971.
267. The Little Colossus of Holography. Business Week, Sept. 11, 1971, p. 122.
268. Holotron Beginning to Enforce Patent Claims in Holograph. Laser Focus, Nov. 1971, p. 22.
269. Engineering Applications of Holography. ARPA Advanced Agenda, Los Angeles, Feb. 16-17, 1972.
270. Courant, R.: Differential and Integrated Calculus. Interscience Publishers, Inc., 1947, pp. 73-75.
271. Reference Data for Radio Engineers. International Telephone and Telegraph Corp., New York, 1957, p. 1005, para. 12.
272. Shulman, A. R.: Optical Data Processing. John Wiley & Sons, Inc., 1970, pp. 312-322.
273. Collier, R. J.; Burckhardt, C. B.; and Lin, L. H.: Optical Holography. Academic Press, 1971, pp. 22-26.
274. Collier, R. J.; Burckhardt, C. B.; and Lin, L. H.: Optical Holography. Academic Press, 1971, pp. 345-350.
275. Smith, H. M.: Principles of Holography. Wiley-Interscience, 1969, pp. 29-31.
276. Caulfield, H. S.; and Lu, S.: The Applications of Holography. Wiley-Interscience, 1970, pp. 43-49.
277. Collier, J. R.; Burckhardt, C. B.; and Lin, L. H.: Color Holography. Optical Holography. Academic Press, 1971, ch. 17.
278. Brown, B. R.; and Lohman, A. W.: Computer Generated Holograms. Engineering Uses of Holography. Cambridge Univ. Press, 1970, p. 77.
279. Meiners, H.: A Reference Source of Demonstration Experiments in Physics. Ronald Press, vol. II (to be published).
280. Leith, E. N.; and Upatnicks, J.: Reconstructed Wavefronts and Communication Theory. JOSA, vol. 52, no. 10, Oct. 1962, pp. 1123-1130.
281. Shulman, A. R.: Analysis of Optical Data Processing Systems. Optical Data Processing. John Wiley & Sons, Inc., 1970, ch. 8, p. 358.
282. Collier, J. R.; et al.: Optical Holography. Academic Press, 1971, pp. 337-345.
283. Goodman, J. W.: Fourier Transforming and Imaging Properties of Lenses. Introduction to Fourier Optics. McGraw-Hill, 1968, ch. 5, pp. 77-100.
284. Shulman, A. R.: The Fourier Transform by Diffraction of Light. Optical Data Processing. John Wiley & Sons, Inc., 1970, ch. 4, pp. 156-223.
285. Collier, R. J.; et al.: Optical Holography. Academic

Press, 1971, pp. 206-210.
286. Collier, R. J.; et al.: Optical Holography. Academic Press, 1971, pp. 273-280.
287. Caulfield, H. S.: The Applications of Holography. Wiley-Interscience, 1970, p. 82.
288. Caulfield, H. S.: The Applications of Holography. Wiley-Interscience, 1970, p. 33.
289. Urback, J. C.: Advances in Hologram Recording Materials. SPIE Seminar Proc., Apr. 1971, p. 17.
290. Shulman, A. R.: Optical Data Processing. John Wiley & Sons, Inc., 1970, pp. 516-523.
291. Goodman, J. W.: Introduction to Fourier Optics. McGraw-Hill, 1968, pp. 171-177.
292. Shulman, A. R.: Image Restoration. Optical Data Processing. John Wiley & Sons, Inc., 1970, app. 16, pp. 672-681.

U.S. GOVERNMENT PRINTING OFFICE : 1974 O—534-778

Page Intentionally Left Blank

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

SPECIAL FOURTH CLASS MAIL
Book

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
NASA-451

U.S.MAIL

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA TECHNOLOGY UTILIZATION PUBLICATIONS

These describe science or technology derived from NASA's activities that may be of particular interest in commercial and other non-aerospace applications. Publications include:

TECH BRIEFS: Single-page descriptions of individual innovations, devices, methods, or concepts.

TECHNOLOGY SURVEYS: Selected surveys of NASA contributions to entire areas of technology.

OTHER TU PUBLICATIONS: These include handbooks, reports, notes, conference proceedings, special studies, and selected bibliographies.

Details on the availability of these publications may be obtained from:

National Aeronautics and
Space Administration
Code KT
Washington, D.C. 20546

Technology Utilization publications are part of NASA's formal series of scientific and technical publications. Others include Technical Reports, Technical Notes, Technical Memorandums, Contractor Reports, Technical Translations, and Special Publications.

Details on their availability may be obtained from:

National Aeronautics and
Space Administration
Code KS
Washington, D.C. 20546

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546